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REVIEW ARTICLE

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Predefined vs data-guided training prescription based on autonomic nervous system variation: A systematic review

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Monitoring variations in the functioning of the autonomic nervous system may help personalize training of runners and provide more pronounced physiological adaptations and performance improvements. We systematically reviewed the scientific literature comparing physiological adaptations and/or improvements in performance following training based on responses of the autonomic nervous system (ie, changes in heart rate variability) and predefined training. PubMed, SPORTDiscus, and Web of Science were searched systematically in July 2019. Keywords related to endurance, running, autonomic nervous system, and training. Studies were included if they (a) involved interventions consisting predominantly of running training; (b) lasted at least 3 weeks; (c) reported pre- and post-intervention assessment of running performance and/or physiological parameters; (d) included an experimental group performing training adjusted continuously on the basis of alterations in HRV and a control group; and (e) involved healthy runners. Five studies involving six interventions and 166 participants fulfilled our inclusion criteria. Four HRV-based interventions reduced the amount of moderate- and/or high-intensity training significantly. In five interventions, improvements in performance parameters (3000 m, 5000 m, Loadmax, Tlim) were more pronounced following HRV-based training. Peak oxygen uptake ($\dot{V}O_{2peak}$) and submaximal running parameters (eg, LT1, LT2) improved following both HRV-based and predefined training, with no clear difference in the extent of improvement in $\dot{V}O_{2peak}$. Submaximal running parameters tended to improve more following HRV-based training. Research findings to date have been limited and inconsistent. Both HRV-based and predefined training improve running performance and certain submaximal physiological adaptations, with effects of the former training tending to be greater.

KEYWORDS
cardiorespiratory fitness, eHealth, endurance, innovation, technology, training, wearable

1 | INTRODUCTION

Training programs balance an individual´s load and recovery procedures in order to promote optimal physiological adaptations, to enhance performance, and to minimize the risk of non-functional overreaching, overtraining, and consequent deleterious effects on health.[1-4]

On the basis of previous theory and/or coaching experience, training programs are predefined in micro-, meso-, and/or macrocycles based on the assumption that improvements in performance, as well as physiological adaptations for any given population, follow a predictable time-course.[5] However, individual responses to predefined training programs vary widely, with some experiencing non-functional overreaching, overtraining, and compromised health.[1,2,6,7] The close physiological monitoring of an athletes' individual response to a training program, in a convenient and unobtrusive manner for both athlete and/or their team, would allow the training program to be appropriately optimized.[1,8]

It has been proposed that functional assessment of the autonomic nervous system (ANS) could provide valuable information concerning certain physiological responses to training.[9,10] The ANS regulates fundamental processes of direct relevance to overall recovery, for example, by controlling the delivery of oxygen and nutrients, removal of waste products that accumulate during exercise, and thermoregulation by the cardiovascular system.[9] Consequently, alterations in ANS regulation reflect certain aspects of the restoration of cardiovascular homeostasis and may aid in identification of balance between training and recovery.[9]

In practice, regulation of the ANS can be assessed by different parameters of heart rate variability (HRV), that is, the variation in the time interval between consecutive heartbeats.[9,11,12] HRV reflects the balance between parasympathetic (vagal) and sympathetic activation, a key aspect of recovery and stress.[13] Thus, negative responses to training and/or non-functional overreaching are associated with reductions in vagal indices of HRV (and therefore impaired recovery), whereas increases in such indices are associated with improvements in performance.[10,14] Consequently, measurement of HRV in association with adaptations and responses to exercise may assist in the planning of training.[1,8]

Different HRV metrics assessing different physiological aspects of the ANS can be derived by the time or frequency domain. It is beyond the scope of this review to list each of these metrics, their physiological context, and limitations in a sufficient manner. In this regard, interested readers are referred to existing articles, which do so eloquently.[12,15,16]

Appropriate assessment of HRV can be difficult to achieve, and interpretation of the data obtained was challenging, since parameters are influenced by a wide variety of factors (eg, noise, light, temperature, posture) and, moreover, vary greatly between individuals.[15,17] In order to ensure high-quality data that allow proper interpretation, all testing must be strictly standardized and each runner needs to establish his/her individual baseline HRV over a certain period of time. For example, a reduction of HRV from a baseline value might be indicative of impaired recovery (eg, from previous training sessions), in which case it might be appropriate to lower the intensity, volume and/or frequency of training.

In the past, HRV has been monitored primarily employing cumbersome laboratory equipment, but as a result of advancements in wearable sensor technology with respect to data collection, design of algorithms, and interpretation of and feedback concerning data related to heart rate, information on HRV is now readily available to both recreational and elite runners.[18] While elite athletes have well-educated and experienced coaches with whom they regularly discuss their training, recreational runners without such guidance may benefit considerably from planning their training on the basis of automated data.[19]

Although recent studies have revealed that training guided by HRV improves certain physiological variables related to performance,[14,20] a systematic review of the literature on recreational runners in this context is lacking. Consequently, the aim here was to systematically review the scientific literature on whether, in the case of runners, training based on vagal indices of HRV improves performance and/or physiological adaptation to a greater extent than predefined training.

2 | METHODS

2.1 | Inclusion criteria

This review sought to identify all scientific publications involving comparisons between predesigned training programs and programs based on variations in the autonomic nervous system of runners.

2.2 | Study populations

All articles reporting on healthy runners of any age and level of performance were included.

2.3 | Interventions

The studies included involved incorporated interventions (a) consisting predominantly of running training with (b) pre- and post-intervention assessment of exercise performance and/or physiological parameters related to running performance; (c) lasting for at least 3 weeks to provide sufficient time for adaptions; (d) performing continuous adjustment of the training of the intervention group based on alterations in

HRV-related parameters; (e) including a control group without such adjustment; and (f) employing wearable sensors to monitor parameters related to HRV.

Our review is not limited to any HRV metric.

2.4 | The outcomes examined

Assessment of performance included maximal parameters (eg, time to volitional exhaustion during an appropriate test). The physiological parameters examined included maximal (eg, $\dot{V}O_{2peak}$) and submaximal (eg, $VO_{2submax}$, HR_{submax}, expressed as percentages of the corresponding maximal values) indicators of cardiometabolic status.

2.5 | Publication status and language

Our search was limited to original articles published in peer-reviewed journals and written in English. References cited by the articles retrieved were also examined for potential relevance. Conference abstracts, dissertations, theses, and other non-peer-reviewed articles were excluded. Figure 1 illustrates the screening and selection process employed.

2.6 | Search strategy

A systematic review was performed in accordance with the Preferred Reporting Items of Systematic Reviews and Meta-analysis (PRISMA).[21] The electronic databases searched included PubMed, SPORTDiscus, and Web of Science (with no restriction concerning publication date), and the following search strings were used: HRV OR heart rate variability OR autonomic nervous system AND guided OR training OR biofeedback AND endurance OR running OR exercise OR aerobic.

2.7 | Selection and quality assessment of articles

The identified articles were incorporated into EndNote X9 (Clarivate Analytics, Philadelphia, USA), where duplicates were eliminated. The titles and abstracts of all potentially relevant articles were screened for eligibility by one of the authors (PD), with independent verification by a second author (BS). The full texts of articles that met the criteria for inclusion were then retrieved and screened. When disagreements between reviewers arose, consensus was achieved through discussion or input from a third author (CZ).

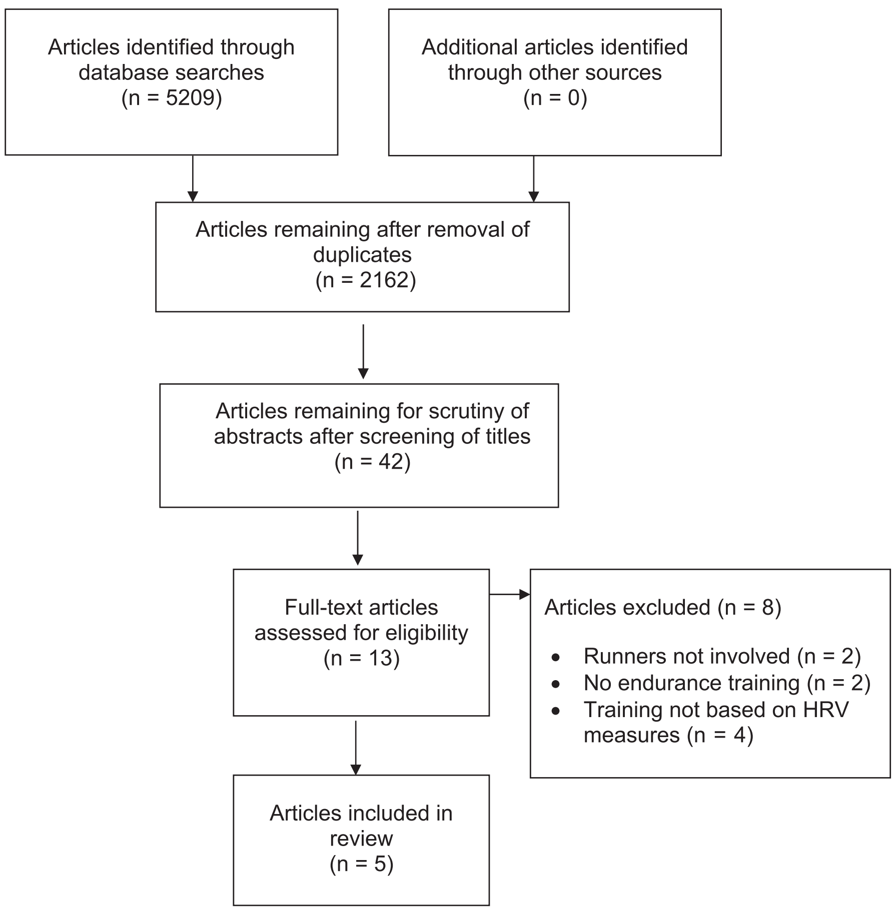

FIGURE 1 Selection of the articles to be analyzed, from initial identification to inclusion

TABLE 1 The scores on the PEDro scale for each study of the articles included

	Item on the PEDro scale											
Article	1[a]	2	3	4	5	6	7	8	9	10	11	Total
[25]	1	1	1	1	0	0	0	1	1	1	1	7
[24]	1	1	1	1	0	0	0	1	1	1	1	7
[20]	1	1	1	1	0	0	0	1	1	1	1	7
[14]	1	1	1	1	0	0	0	1	1	1	1	7
[8]	1	1	1	1	0	0	0	1	1	1	1	7

[a]Not included in calculation of the total PEDro score.

2.8 | Data extraction and analysis

From the articles thus selected, the first author (PD) extracted data and another author (BS) confirmed the accuracy of this extraction. The information extracted concerned details of publication (authors, year, journal, publication date), characteristics of the study population (age, sample size, sex), study design (duration of intervention, nature of the training planned, description of HRV measurements, criteria on which decisions to modify training were based), and outcomes (difference between the intervention and control groups with respect to parameters related to performance, as well as physiological and biomechanical parameters).

2.9 | Assessment of methodological quality

The methodological quality of the articles included was assessed by application of the Physiotherapy Evidence Database (PEDro) scale (described in detail elsewhere[22,23]). In brief, for each of the 10 criteria fulfilled (eg, blinding of subjects, blinding of assessors, the similarity of the subjects in the experimental and control groups prior to the intervention), one point was given, the total possible score being 10 points.[22,23] The risk of bias was assessed independently by two of the authors (PD and CZ), with any disagreements again being resolved by consensus or through discussion with a third author (BS).

3 | RESULTS

3.1 | Study characteristics

Of the 5209 articles initially identified, only five fulfilled all the criteria for inclusion in the analysis. All exhibited a PEDro score of 7 and were published between 2007 and 2017 (Table 1).

The study characteristics, including the predefined training schedule, assessment of HRV, and the manner in which the training loads were altered, are summarized in Table 2.

One study involved two intervention groups whose training was adjusted on the basis of HRV.[24]

The interventions ranged from four[20] to eight[8,14,24,25] weeks, and a total of 172 participants (80 women) were involved. The baseline $\dot{V}O_{2peak}$ ranged from 49 to 56 mL kg^{-1}•min^{-1} for the male,[14,20,24,25] and 35-37 mL kg^{-1} min^{-1} for the female participants[24]; in one study, the participants' $\dot{V}O_{2peak}$[8] prior to the investigation was not reported. Three studies involved only running,[8,20,25] another one mainly running (~60% of the training sessions, with ~13% cycling and ~27% other),[24] and one involved running and five sessions of strength training during the 8-week intervention.[14]

In four studies, HRV was assessed in the morning,[14,20,24,25] and in the fifth in the afternoon/evening.[8] Different HRV parameters were reported: Three studies measured the root mean sum of squared differences (rMSSD),[8,14,25] one high-frequency power,[20] and the remaining SD1 (standard deviation of the instantaneous beat-to-beat variability in the R-R interval, obtained from Poincaré plots).[24] All of the studies assessed individual HRV during a baseline period of 3,[14] 7[25] or 10 days[8,20,24] immediately prior to the period of intervention.

Three studies employed wearables manufactured by Polar Electro (Polar Electro OY, Kempele, Finland),[8,20,24] a wearable manufactured by Garmin (Garmin Ltd, Schaffhausen, Switzerland),[14] and another a Omegawave Ltd device (Omegawave Ltd., Helsinki, Finland).[25] All of these wearables, which are commonly employed to assess HRV in athletes, use a chest belt to record relevant parameters.

The major outcomes assessed and compared with performance and physiological and biomechanical parameters included maximal running velocity (v_{max})[14,20] or maximal load on a cycle ergometer ($Load_{max}$)[24]; mean velocity during a 3000-m time-trial of running[25]; time required to complete a 5000-m running time-trial[8]; time until volitional exhaustion at maximal running velocity[8]; peak oxygen consumption[14,20,24,25]; velocity at the first (LT_1) and second (LT_2)

TABLE 2 Characterization of the studies analyzed

Participants				HRV				
Article	**N (male, female)**	**Level of performance**	**Age (years)**	**Predefined training (duration)**	**Monitoring technology**	**HRV metric**	**Measurement employed to adapt training**	**Modification of training**
[25]	20, 20	Recreational runners VO2peak: 49 ± 4 mL•kg^{-1} min^{-1}	34 ± 8	Periodization: 3 intense training weeks, 1 easy training week, progressively increasing intensity 1 session of activity other than running each week 38 training sessions (8 wk) half at low intensity (below LT1), half at moderate or high intensity	Omegawave Pro Mobile System (Omegawave Ltd., Helsinki, Finland)	rMSSD	Every morning 4-min supine position 7-d moving window of rMSSD was calculated to guide training	4-wk baseline period immediately before the intervention Smallest worthwhile individual changes calculated from the baseline data If the 7-d moving rMSSD window was less than the smallest worthwhile change: low-intensity training. Otherwise high- or moderate-intensity training
[24]	14, 14	Recreational runners VO2peak: Men: 50 ± 6 mL kg^{-1} min^{-1} Women: 35 ± 5 mL kg^{-1} min^{-1}	• Men: • 35 ± 4 Women • 33 ± 4	• 2 × 40 min at ~70% HR_{max}3 × 30 min at ~85% HR_{max} (+5 min warm-up and cool-down) (8 wk)	Polar RS800 (Polar Electro OY, Kempele, Finland)	SD1	Every morning 3-min standing	Individual baseline data from the preceding 10 d (moving window) If no significant decrease in SD1 on any given day: vigorous exercise Moderate exercise after 2 sessions of vigorous exercise Significant decrease in SD1 on any given day: moderate-intensity exercise Significant decrease in SD1 on 2 consecutive days: rest for maximally 2 consecutive days, followed by moderate-intensity exercise

(Continues)

TABLE 2 (Continued)

Participants				*HRV*				
Article	**N (male, female)**	**Level of performance**	**Age (years)**	**Predefined training (duration)**	**Monitoring technology**	**HRV metric**	**Measurement employed to adapt training**	**Modification of training**
[24]	0, 10	VO2peak: Female: 37 ± 5 mL kg^{-1} min^{-1}	35 ± 4	2 × 40 min at ~70% HRmax 3 × 30 min at ~85% HRmax (+5 min warm-up and cool-down) (8 wk)	Polar RS800 (Polar Electro OY, Kempele, Finland)	SD1	Every morning 3-min standing	Individual baseline values from the preceding 10 d Vigorous exercise prescribed only when HRV increased Moderate intensity prescribed if HRV was unchanged Moderate exercise after 2 sessions of vigorous exercise
[20]	26, 0	Runners VO2peak: ~56 ± 4 mL kg^{-1} min^{-1}	35 ± 4	Day 1: Low-intensity exercise; Day 2: high-intensity exercise; Day 3: High-intensity exercise; Days 4-6: repeat Days 1-3; Day 7: rest High intensity: 30 min at 85% HR_{max} (+5 min warm-up and cool-down at 65% HR_{max}) Low intensity: 40 min at 65% HR_{max} (4 wk)	Polar S810i (Polar Electro OY, Kempele, Finland)	High-frequency power (HF_{power}; 0.15-0.40 Hz)	Every morning 5-min standing	Individual baseline data collected on the preceding 10 d (moving window) If HFpower increased significantly: 2 d of high-intensity exercise followed by low-intensity exercise Rest after 9 consecutive days of training HR_{power} decreased significantly on any given day: low-intensity training HF_{power} decreased significantly for 2 consecutive days: rest for maximally 2 consecutive days, followed by low-intensity training

(Continues)

TABLE 2 (Continued)

Participants				*HRV*				
Article	**N (male, female)**	**Level of performance**	**Age (years)**	**Predefined training (duration)**	**Monitoring technology**	**HRV metric**	**Measurement employed to adapt training**	**Modification of training**
[14]	32, 0	Runners VO2peak: ~53.6 mL kg^{-1} min^{-1}	19-37	Low-intensity sessions: < individual aerobic threshold Duration: self-selected between 30-90 min High-intensity interval sessions: 4 × 4 min at 90%-95% HR_{max} (3 min recovery); 3 × 10 × 30 s at 95% v_{max} (3 min recovery between sets) 5 strength training sessions (including leg press, knee flexion, upper-body exercises, bench step, and half squat) (8 wk)	Garmin 920 XT (Garmin Ltd, Schaffhausen, Switzerland)	Quick recovery test" based on rMSSD (Firstbeat Technologies Ltd, Jyväskylä, Finland)	Supine position 3-min data collection	Training was scheduled in blocks In-between these blocks, HRV data were used to modify training HRV below baseline: low-intensity training HRV above baseline: the next block could be started
[8]	0, 36	Runners untrained	18-35	3 training sessions per week 12 sessions moderate intensity (6 × 30 min at 75% v_{max}; 6 × 40 min at 75% v_{max}); 12-session vigorous intensity (interval series of total duration comparable to that of the moderate-intensity training) (at 100% V_{peak}) 8 wk	Polar RS800cx (Polar Electro OY, Kempele, Finland)	rMSSD	Measured in the afternoon/evening	Baseline: 10-day moving window If rMSSD was <baseline: moderate-intensity exercise If rMSSD was >SD greater than baseline mean: high-intensity exercise

Abbreviations: HF_{power}, high-frequency power; HR_{max}, individual maximal heart rate; HRV, heart rate variability; LT1, first lactate threshold; rMSSD, root mean sum of squared differences; SD, standard deviation; v_{max}, maximal running velocity; VO2peak, individual maximal systemic oxygen uptake; Wk, week.

lactate thresholds[14]; and ventilatory threshold (VT).[20] All outcomes are summarized in Tables 3 and 4.

3.2 | Training parameters

As documented in Table 2, four HRV-based interventions involved significantly fewer moderate- and/or high-intensity sessions of exercise than the predefined training[8,20,24,25]; one more moderate-intensity sessions[24]; and in one case, there was no difference.[14]

3.3 | Performance

Table 3 summarizes performance (eg, t3000 m, 5000 m, $Load_{max}$, tlim at v_{max}) following training that was predefined or adjusted on the basis of HRV, with statistical analyses of the differences within and between these two groups. Comparison revealed non-significant differences between these groups with respect to two parameters related to $Load_{max}$[24]; a trivial effect (ES 0.00) on t3000 m[14]; significant differences in two other parameters related to $Load_{max}$[20,24]; and small-to-large effects (ES = 0.29-0.93) on 3000 m, 5000 m, v_{max}, and tlim at v_{max} speaking in favor for HRV-guided training.[8,14,25]

3.4 | Maximal and submaximal physiological variables

Table 4 summarizes the maximal and submaximal values for performance parameters obtained following training that was predefined or adjusted on the basis of HRV, with statistical analyses of the differences within and between these two groups. In the case of $\dot{V}O_{2peak}$, no significant difference was observed in three cases,[20,24] a small positive effect of HRV-guided training (ES 0.42) in one case,[14] and a small negative effect (ES 0.26) of such training in another.[25] In connection with one intervention, $\dot{V}O_{2peak}$ was not assessed.[8] Of the three studies in which the submaximal physiological parameters LT_1, LT_2 and VT were assessed, two reported small and moderate positive effects (ES = 0.25-0.54) of HRV-guided training,[8,14,25] while in the third, no significant differences were observed.[14]

4 | DISCUSSION

This systematic review revealed that both predefined and HRV-based training enhanced running performance, as well as several relevant physiological variables. The major comparative findings were as follows:

1. Although their training load was higher relative to the baseline period, 4 of 6 HRV-based training interventions involved fewer sessions of moderate- and/or high-intensity exercise than predefined training.
2. In 5 of the 6 interventions, improvements in performance were more pronounced following HRV-based training (according to Tables 1 and 2: approximately + 10%) than after the predefined training (mean approximately + 6%).
3. Both HRV-based and predefined training improved $\dot{V}O_{2peak,}$ with no clear difference between the two in this respect.
4. Submaximal running outcomes (ie, LT_1, LT_2, VT) improved to a greater extent with HRV-based training (mean approximately + 5%) than predefined training (mean approximately 3%).
5. These conclusions should be considered as somewhat preliminary, since the research available in this area is both limited and inconsistent.

4.1 | Outcome measures

With the HRV-based training, the load (eg, intensity, volume, and frequency of training sessions) decreased as HRV declined. This was not unexpected since HRV is typically reduced following an elevation in training load.

Typically, HRV is reduced following an elevation of training load and, vice versa, this variability is greater with lower training loads.[11] In fact, according to the present analysis, the load (eg, intensity, volume, and frequency of sessions) adjusted on the basis of HRV decreased as this variability declined. Nonetheless, although both forms of training improved running performance, most parameters related to performance were improved to a greater extent following HRV-based training.

4.2 | Analysis of the variation in outcome measures

From our present analysis, it remains unclear whether the improvements in performance (eg, time to exhaustion or time required to run 5000 m) and physiological outcomes (eg, $\dot{V}O_{2peak}$) obtained with HRV-based training are less variable, with fewer non-responders, than in the case of predefined training. Vesterinen and colleagues[25] reported a trend toward less variation in 3000-m time-trial performance following HRV-based training (−1% to 6%) versus after predefined training (−4% to 8%). The former involved 5-24 high-intensity sessions versus the 11-21 high-intensity sessions of predefined training, and the authors argue that this indicates that the timing of high-intensity sessions in HRV-based training

TABLE 3 Training and Performance parameters following training based on HRV and predefined training

Study	Training parameters: Differences between the HRV-based and predefined training programs	Performance: HRV PRE	Performance: HRV POST	Performance: HRV Change (%)	Performance: Predefined PRE	Performance: Predefined POST	Performance: Predefined Change (%)	The effects of HRV-based and predefined training: Performance
[25]	Sessions of moderate and high intensities: HRV-based: 13.2 ± 6.0* Predefined: 17.7 ± 2.5 Effect size: 0.98 (large)	3000 m ($km•h^{-1}$): 15.4 ± 1.6	3000 m ($km•h^{-1}$): 15.7 ± 1.5	3000 m (%) 2.1 ± 2.0*	3000 m ($km•h^{-1}$) 15.0 ± 1.6	3000 m ($km•h^{-1}$) 15.2 ± 1.5	3000 m (%) 1.1 ± 2.7 (n.s)	3000 m ($km•h^{-1}$): 0.42 (small effect)
[24]	Number of moderate-intensity sessions per week: HRV-based: Men: 2.7 ± 0.2* Women: 2.5 ± 0.3* Predefined: Men: 2.1 ± 0.1 Women: 2.2 ± 0.2	$Load_{Max}$ (Watt): Men: 270 ± 29 $Load_{Max}$ (Watt): Women: 174 ± 28	$Load_{Max}$(Watt): Men: 300 ± 25 $Load_{Max}$ (Watt): Women: 189 ± 25	$Load_{Max}$(%): Men: +11.1 $Load_{Max}$ (%): Women: +8.6	$Load_{Max}$(Watt): Men: 275 ± 28 $Load_{Max}$ (Watt): Women: 179 ± 32	$Load_{Max}$(Watt): Men: 293 ± 35 $Load_{Max}$ (Watt): Women: 198 ± 35	$Load_{Max}$(%): Men: 6.5* $Load_{Max}$ (%): Women: 10.6*	$Load_{Max}$ (Watt): Men: $P < .1$ $Load_{Max}$ (Watt): Women: n.s.
[24]	Number of intense sessions of exercise per week: HRV-based: 1.8 ± 0.3* Predefined: 2.8 ± 0.6	$Load_{Max}$ (Watt): Women: 177 ± 26	$Load_{Max}$ (Watt): Women: 194 ± 23	$Load_{Max}$ (%): +9.6	$Load_{Max}$ (Watt): Women: 179 ± 32	$Load_{Max}$ (Watt): Women: 198 ± 35	$Load_{Max}$ (%): Women: 10.6*	$Load_{Max}$ (Watt): n.s.
[20]	Number of high-intensity sessions of exercise per week: HRV-based: 3* Predefined: 4	v_{max} ($km•h^{-1}$): 15.5 ± 1.0	v_{max} ($km•h^{-1}$): 16.4 ± 1.0	v_{max} (%): +5.8*	v_{max} ($km•h^{-1}$): 15.1 ± 1.3	v_{max} ($km•h^{-1}$): 15.7 ± 1.2*	v_{max} (%): 3.9*	v_{max} ($km•h^{-1}$) $P < .05$
[14]	Training sessions per week HRV-based: 6.3 ± 1.4 (3 ± 3% in HR Zone 3) Predefined: 6.1 ± 0.4 (4 ± 3% in HR Zone 3)	3000 m (s): 673 ± 50 v_{max} ($km•h^{-1}$): 17.6 ± 1.3	3000 m (s): 638 ± 52 v_{max} ($km•h^{-1}$): 18.5 ± 1.2	3000 m (%): 5.2* v_{max} (%) +5.1*	3000 m (s): 667 ± 47 v_{max} ($km•h^{-1}$): 18.0 ± 1.1	3000 m (s): 632 ± 41 v_{max} ($km•h^{-1}$): 18.5 ± 1.2*	3000 m (%): 5.2* v_{max} (%): 2.7*	3000 m: 0.00 (trivial) v_{max} ($km•h^{-1}$): 0.95 (large effect)

(Continues)

TABLE 3 (Continued)

Study	Training parameters: Differences between the HRV-based and predefined training programs	Performance: HRV PRE	HRV POST	HRV Change (%)	Predefined PRE	Predefined POST	Predefined Change (%)	The effects of HRV-based and predefined training: Performance
[8]	Total relative amount of moderate-intensity sessions: HRV-based: 36.7 ± 5.5*; Predefined: 50 ± 0	v_{max} (km•h^{-1}): 10.9 ± 1.2	v_{max} (km•h^{-1}): 11.9 ± 0.9	v_{max} (km•h^{-1}): +10.0 ± 7.3*	v_{max} (km•h^{-1}): 11.0 ± 1.4	v_{max} (km•h^{-1}): 11.9 ± 1.4	v_{max} (%) 8.2 ± 4.7%*	v_{max} (km•h^{-1}): 0.29 (small effect)
		tlim at v_{max} (min): 5.1 ± 1.3	tlim at v_{max} (min): 6.1 ± 1.7	tlim at v_{max} (%): +23.6 ± 31.9*	tlim at v_{max} (min): 5.4 ± 1.7	tlim at v_{max} (min): 4.8 ± 1.6	tlim at v_{max} (%): 26.7 ± 31.2 (n.s.)	T_{lim} at v_{max} 0.93 (moderate effect)
		t5 km (min): 36.3 ± 4.5	t5 km (min): 29.8 ± 2.4	t5 km (%): −17.5 ± 5.6*	t5 km (min): 35.5 ± 5.0	t5 km (min): 30.5 ± 4.3	t5 km (%): −14.0 ± 4.7*	t5 km: 0.67 (moderate effect)

Abbreviations: 3000 m, time to run 3000 m; ES, effect size; LoadMax, maximal load in a cycle ergometer test; nr, not reported; n.s., not significant; t5000 m, time to run 5000 m; tlim, time run at maxi + mal velocity; v_{max}, maximal running velocity.

*Sign. Different.

diminishes variation in adaptation.[25] In this connection, controlled cross-over studies (eg, controlling for inter-individual differences such as genetic predisposition) of intra-individual performance and physiological responses are warranted.

4.3 | Increases in training load

Certain aspects of the methodological approaches employed to elucidate potential differences in physiological responses to HRV-based and predefined training need to be considered. In most cases, the individual increases in training load from baseline to the intervention period were unclear, since, unfortunately, baseline characteristics were not reported in detail. This not only makes comparisons between studies difficult, but also prevents reliable evaluation of the effectiveness of HRV-based training. To clearly establish differences in the responses to HRV-based and predefined training, the increase in training load from baseline to intervention must be known (eg, determined by training impulse [TRIMP] calculations[6]), since an increased volume, intensity, and/or frequency should result in activation of the expression of various genes and specific physiological adaptations.

Differences in the type of training load applied are also important. It is well known that equal training loads (based on, eg, TRIMP or % $\dot{V}O_{2peak}$) of different sorts may result in heterogeneous metabolic challenges and, consequently, substantially different physiological and performance responses.[6,26]

4.4 | Different HRV metrics

As briefly mentioned in Introduction, different metrics from time or spectral analysis can be derived from HRV and some reflect more cardiac sympathetic activity, while others tend to reflect cardiac parasympathetic (vagal) activity. The interventions included in this systematic review employed either rMSSD, SD1 obtained from Poincaré plots, or high-frequency power. These metrics aim at indexing cardiac parasympathetic (vagal) activity and are highly correlated.[27,28] The current literature in this field is limited regarding which of these parameters is most suitable to guide training; however, from a practical point of view previous reports[17] prefer rMSSD and SD1 to other metrics since (i) rMSSD and SD1 can be obtained over limited time periods (eg, 10 s to 1 min), and (ii) compared to spectral indices, these metrics are less sensitive to confounding breathing patterns.

4.5 | Confounding factors

Since measurements of HRV is also influenced by factors not directly related to training, such as psychological (eg, work and/or academic) stress,[9] we cannot be certain what the alterations in ANS underlying the HRV-based training actually reflect. Arguably, the source of stress may be irrelevant, since training at high intensities does not produce optimal outcomes, and it therefore appears logical to recover with low-intensity exercise or no exercise at all.[25] Nevertheless, identifying the source of stress might allow reduction of its impact, thereby improving recovery and/or training strategies. For this purpose, more subjective and/or objective data on the individual level are required.[1] In addition, the lack of blinding concerning the identity of the groups in all of the studies described here might have influenced the outcomes.

Previously, the values for parameters related to HRV have been shown to usually be lower when the heart rate itself is relatively high and vice versa.[29] Thus, these values must be interpreted in relation to mean heart rate.[30]

With the growing number of novel wearable sensors and algorithms[31] that allow monitoring of the ANS, HRV-based training becomes available to more and more individuals. In this context, runners without the guidance of a coach might benefit most.[19] Accordingly, on the basis of our present findings, we make the following practical recommendations for researchers and individuals interested in HRV-based training:

4.5.1 | Recommendations for researchers

(i) Controlled cross-over studies designed to assess intra-individual differences in responses to HRV-based training and predefined training should be performed.
(ii) The possibility that variation in physiological and performance responses to HRV-based training is less than in the case of predefined training needs to be examined.
(iii) Baseline training characteristics and individual increases in training load during the intervention period should be reported routinely.
(iv) Procedures designed to assess whether the stress on the ANS stems from training and/or other stressors, and whether the source of stress influences responses to HRV-based training should be incorporated.
(v) All monitoring procedures should be standardized as fully as possible as also recommended elsewhere,[17] the participants should be blinded as to whether they are performing predefined or HRV-guided training, and, as also mentioned above, HRV should be interpreted in relation to mean heart rate. Future sensor technologies, such as photoplethysmography, may allow perturbations in the ANS to be monitored more reliably, practically, and frequently[32-35] but its application needs scientific evaluation.

4.5.2 | Recommendations for coaches and individual runners

HRV-based training should be used with care. In this context, numerous confounding factors — such as post-exercise intake of fluid, sex, age and gender, baseline physical fitness, training status, training context, body position, and environmental factors (eg, hypoxia or heat) — need to be taken into consideration.[9,10,17] Measurements of HRV in the morning and, potentially, while standing are recommended.[2,17]

Although daily monitoring of HRV may be inconvenient, monitoring at least 3 or 4 times each week should be feasible.[17] Among the various approaches to assess HRV (eg, frequency domain indices), from a practical perspective time domain indices (eg, the square root of the mean of the sum of squares differences between adjacent R-R intervals (rMSSD)) and SD1 (standard deviation of the variability of the instantaneous beat-to-beat R-R interval as determined from Poincaré plots)) are the most reliable.[2,17]

Since inter-individual differences in HRV are considerable, we strongly advise establishing a baseline of "normal" daily fluctuations for each individual. The articles analyzed here all utilized different baseline periods to assess these daily fluctuations, and currently, to the best of our knowledge, no consensus on this matter exists.

Finally, only a few wearable sensors designed to monitor HRV have yet been validated and consumers should select valid and reliable technology carefully.[31]

5 | CONCLUSIONS

On the basis of this review, we conclude that 4-8 weeks of either HRV-based training or predefined training improves running performance and certain related physiological parameters (eg, VO_{2peak}, $VO_{2submax}$). Enhancement of performance and submaximal physiological adaptations appear to be more pronounced with HRV-based training which involves fewer sessions of moderate and/or intense training. These conclusions should be considered to be somewhat preliminary, since the available research in this area is both limited and inconsistent.

6 | PERSPECTIVE

As a process, training programs should be frequently adjusted in order to maintain an individual´s balance between load and recovery and to enhance performance optimally. Information based on the day-to-day variation of the autonomic nervous system was proposed as potentially beneficial for such adjustments. This review identified studies in runners comparing physiological adaptations and/or improvements in

TABLE 4 Physiological parameters following training based on HRV and predefined training

	$\dot{V}O_{2peak}$ (mL•kg^{-1}•min^{-1})						
	HRV			Predefined training			Difference between HRV and predefined training
Study	Pre	Post	Change (%)	Pre	Post	Change (%)	
[25]	54.4 ± 6.2	56.4 ± 7.0	+3.7 ± 4.6 (%)*	53.0 ± 5.8	55.5 ± 5.8	+5.0 ± 5.2 (%)*	0.26 (small negative effect size)
[24]	Men: 50 ± 6 Women: 36 ± 4	Men: 54 ± 6 Women: 39 ± 3	Men +8.0 (%) Women: +8.3 (%)	Men: 50 ± 7 Women: 35 ± 5	Men: 53 ± 7 Women: 37 ± 4*	Men: +6.0(%)* Women: +5.7(%)*	Men: n.s. Woman: n.s.
[24]	Women: 37 ± 5	Women: 40 ± 5	Women: +8.1 (%)	Women: 37 ± 5	Women: 40 ± 5	Women: +8.1 (%)	VO2peak: n.s.
[20]	56 ± 4	60 ± 5	+7.1 (%) *	54 ± 4	55 ± 3	+1.9 (%)	n.s.
[14]	53.6 ± 4.2	56.7 ± 3.4	+5.7 (%)*	52.2 ± 4.1	56.4 ± 4.7*	+8.0(%)*	0.42 (small effect)
[8]	nr	nr	nr	nr	nr	nr	nr

Abbreviations: 3000 m, time to run 3000 m; ES, effect size; m nr =not reported; n.s. not significant; VO2peak, individual peak systemic oxygen uptake.
*Sign. Different.

performance following training (average duration of intervention 7.3 ± 1.6 weeks) based on the responses of the autonomic nervous system (ie, changes in heart rate variability) and predefined training, while both HRV-based and predefined training improve running performance and certain submaximal physiological adaptations, with the effects of the former training tending to be greater. Due to advancements in wearable sensor technology, information on HRV is now readily available to both recreational and elite runners [14], aiding them to guide training if data are assessed and interpreted correctly.

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CONFLICT OF INTEREST

PD, CZ, JLR, HCH, and BS: no conflicts of interest to declare.

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Physiological submaximal parameters						
HRV			**Predefined training**			**Difference between HRV and predefined training**
Pre	**Post**	**Change (%)**	**Pre**	**Post**	**Change (%)**	
LT1 (km•h^{-1}) 11.0 ± 1.2	LT1 (km•h^{-1}) 11.3 ± 1.2	LT1 (%) +2.8 ± 3.7*	LT1 (km•h^{-1}): 10.6 ± 1.4	LT1 (km•h^{-1}) 10.7 ± 1.5	LT1 (%) +1.0 ± 2.9	LT1 (km•h^{-1}): 0.54 (moderate)
LT2 (km•h^{-1}) 13.4 ± 1.4	LT2 (km•h^{-1}) 13.8 ± 1.3	LT2 (%) +2.6 ± 3.3*	LT2 (km•h^{-1}) 12.8 ± 1.6	LT2 (km•h^{-1}) 13.1 ± 1.5	LT2 (%) +1.9 ± 2.2*	LT2 (km•h^{-1}): 0.25 (small)
nr	nr	nr	nr	nr	nr	nr
nr	nr	nr	nr	nr	nr	nr
nr	nr	nr	nr	nr	nr	nr
VT (km•h^{-1}): 12.0 ± 0.6	VT (km•h^{-1}): 12.7 ± 0.5	VT (%) +5.8 *	VT (km•h^{-1}): 11.8 ± 0.9	VT (km•h^{-1}): 12.2 ± 0.9	VT (%) +3.4	VT (km•h^{-1}): n.s.
LT1 (km•h^{-1}): 11.0 ± 1.5	LT1 (km•h^{-1}): 11.8 ± 1.1	LT1 (%) +7.3*	LT1 (km•h^{-1}): 11.6 ± 1.2	LT1 (km•h^{-1}): 12.2 ± 1.2	LT1 (%) +5.1*	LT1: 0.32 (small effect)
LT2 (km•h^{-1}): 14.1 ± 1.0	LT2 (km•h^{-1}): 15.0 ± 1.1	LT2 (%) +6.4*	LT2 (km•h^{-1}): 14.7 ± 0.9	LT2 (km•h^{-1}): 15.3 ± 1.2	LT2 (%) +4.0*	LT2: 0.37 (small effect)
nr	nr	nr	nr	nr	nr	nr

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