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SYSTEMATIC REVIEW

Heart Rate Variability and Swimming

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Abstract
Background and Objectives Professionals in the domain of swimming have a strong interest in implementing research methods in evaluating and improving training methods to maximize athletic performance and competitive outcome. Heart rate variability (HRV) has gained attention in research on sport and exercise to assess autonomic nervous system activity underlying physical activity and sports performance. Studies on swimming and HRV are rare. This review aims to summarize the current evidence on the application of HRV in swimming research and draws implications for future research.
Methods A systematic search of databases (PubMed via MEDLINE, PSYNDEX and Embase) according to the PRISMA statement was employed. Studies were screened for eligibility on inclusion criteria: (a) empirical investigation (HRV) in humans (non-clinical); (b) related to swimming; (c) peer-reviewed journal; and (d) English language.
Results The search revealed 194 studies (duplicates removed), of which the abstract was screened for eligibility. Fourteen studies meeting the inclusion criteria were included in the review. Included studies broadly fell into three classes: (1) control group designs to investigate between-subject differences (i.e. swimmers vs. non-swimmers, swimmers vs. other athletes); (2) repeated measures designs on within-subject differences of interventional studies measuring HRV to address different modalities of training or recovery; and (3) other studies, on the agreement of HRV with other measures.
Conclusions The feasibility and possibilities of HRV within this particular field of application are well documented within the existing literature. Future studies, focusing on translational approaches that transfer current evidence in general practice (i.e. training of athletes) are needed.

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1 Introduction

Swimming is of the most practiced and most popular forms of physical activity in the EU [1] and the US [2]. Research has addressed the beneficial health effects of swimming [3] (e.g. in the prevention and treatment of cardiovascular-related diseases [4–7], and in patients with respiratory impairments such as asthma [8–11]), as well as its psychological (e.g. mood altering) [12–14] and adverse health effects [15–22].

Besides these fields of research, professionals in the domain of swimming have a strong interest in implementing research methods in evaluating and improving training methods to maximize athletic performance and competitive outcome. Of particular interest are methods for the assessment of bio-behavioral (e.g. metabolic and cardioventilatory responses [23]) and endocrinological (e.g. cortisol, testosterone, insulin [24–26]) markers to investigate the effects of swim training and their relation to performance outcome. Traditionally, research on exercise physiology utilized a brainless model of human exercise performance [27], solely focusing on mechanisms of muscle fatigue. In comparison, contemporary research emphasizes the central neural networks involved in the regulation of exercise performance [27]. In particular, the autonomic nervous system (ANS) has gained huge attention for its vital role in the homeostatic regulation of the organism to functionally adapt to the demands of the environment (e.g. exercise and sport) [28, 29].

While the effects of swimming on autonomic outflow have been studied [30] using blood pressure (BP; e.g. Nualnim et al. [6, 31] and Cox et al. [6, 31]), heart rate (HR; e.g. Jung and Stolle [32–34], Butler and Woakes [32–34], and Hauber et al. [32–34]) or similar parameters of cardiovascular activity, HR variability (HRV) in athletes has only received attention over the last decade [35, 36]. The characteristic beat-to-beat variation in HR represents the continuous interplay between the sympathetic and parasympathetic branches of the ANS in regulating HR. Increases in sympathetic activity are associated with increases in HR, while relative increases in parasympathetic activity are associated with decreases in HR. In the resting condition the heart is under tonic inhibitory control (parasympathetic dominance over sympathetic influences) [37]. Sympathetic effects are slow (on the timescale of seconds), while parasympathetic effects are faster (on the timescale of milliseconds [ms]) [38]. Thus, the analysis of changes in the beat-to-beat variation of the heart is therefore a traceable proxy measure of the ANS, in particular parasympathetic vagal activity. Exercise training (in particular endurance training) is associated with increases in parasympathetic activity, indexed by greater vagally-mediated HRV [39–44]. The study of HRV in athletes has been considered a valuable tool to investigate long-term changes related to exercise training and ANS activity during exercise [32], as well as to monitor performance, fitness and freshness [45].

Furthermore, a rationale to study HRV in sport research is given by findings that emphasize anatomical and functional differences of the cardiovascular system between competitive athletes and untrained individuals [46]. While athletes, independent of their sporting activity, have lower resting HR, recent research on exercise-induced cardiac remodeling [47] supports the existence of an endurance-trained and a strength-trained heart in athletes performing dynamic and static sports [48], leading to training-specific changes in cardiac structure and function [49]. Swimming differs from other popular exercise modalities in many aspects (i.e. posture, water immersion, upper and lower body involvement, temperature). The cardiac adaptations to swim training are characterized by left ventricular dilatation, normal wall thickness to dimension ratio, and increased stroke volume with normal diastolic filling [30]. Furthermore, evidence supports differences between long- and short-distance swimmers [50]. However, studies on the effect of swimming on HRV and the usefulness of HRV methods within the professional application are rare. Within this systematic review, we attempt to summarize current findings on the influence of swimming on HRV and the potential usefulness of HRV as a tool in evaluating swim training and maximizing performance.

2 Methods

2.1 Search Strategy

This review uses a systematic approach, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [51], to synthesize research on HRV and swimming. The following computerized databases were searched from 1 January 1996 to 31 July 2013: PubMed via MEDLINE, PSYNDEX and Embase (see Electronic Supplementary Material [ESM] Appendix for search terms and strategies applied, by database). The search was restricted to publications published within that timeframe, since the first guidelines on standards of measurements, physiological interpretation and clinical use of HRV were published in 1996 [52]. Articles were considered for inclusion if they measured HRV (search term keyword: 'heart rate variability' OR 'HRV') and (AND) had a focus on swimming or swimmers (search term keywords: 'swim*'; see ESM Appendix for detailed search strategy). Details were recorded regarding the number of studies found by database and search term, as depicted within the flowchart (see Fig. 1).

The abstracts of the manuscripts were then independently screened for eligibility by two authors (JK and MNJ). Differences in initial study identification and selection for review were compared and deviations were discussed until consensus on the disposition of each study under question could be reached. Screening was based on the following criteria: (a) empirical investigation with HRV measures taken in humans from non-clinical samples; (b) specifically related to swimming (i.e. reported training effects in swimmers); (c) published in a peer-reviewed journal; and (d) published in English. Included papers were reviewed in full text for information on (1) study design and subjects; (2) swimming variables (i.e. elite swimmers,

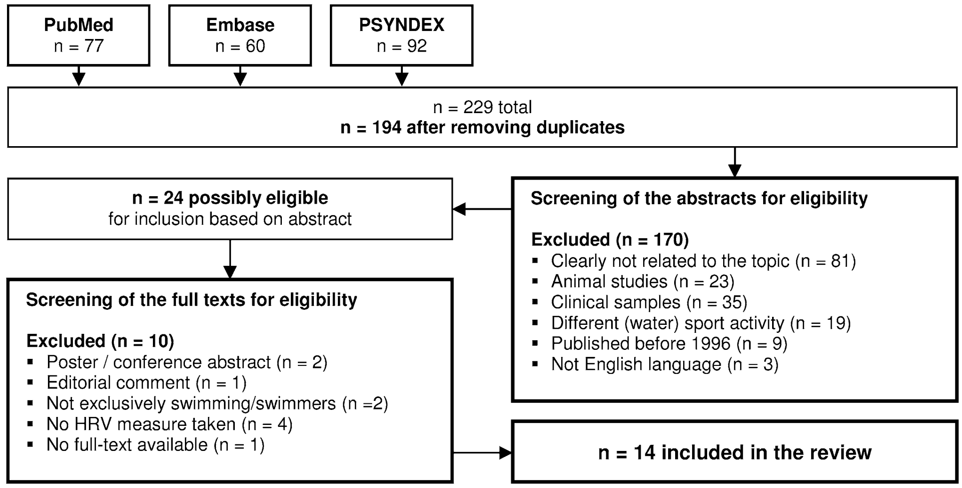

Fig. 1 Search flow diagram. *HRV* heart rate variability

training frequency); (3) method of HRV measurement; (4) data on HRV time domain measures; and (5) data on frequency domain measures. The few differences in evaluation were addressed, producing the consensus presented in Fig. 1. The number of studies meeting the pre-specified inclusion criteria, number of studies excluded, and reasons for exclusion were recorded.

2.2 Data Extraction

Study information on author, country, study population, sample size, sex ratio, age of participants, and main study focus were extracted from the papers retrieved in full text. Furthermore, details regarding the HRV measures obtained from data sets were extracted and main findings or reported effects were derived from the papers retrieved in full text and summarized within a comprehensive table (Table 1). Studies were classified and summarized by their study design (i.e. control group, crossover, other).

3 Results

The search of the selected databases revealed 229 articles (Fig. 1). A total of 194 articles were considered for inclusion in the review after removing duplicates. The abstracts of all articles were retrieved for further screening of eligibility, leaving 24 articles for further consideration. These were retrieved in full text if possible. A total of 14 studies [53–66] were finally included in the systematic review (Fig. 1; Table 1).

3.1 Heart Rate Variability Measures

Besides basic measures of HR (i.e. beats per minute [BPM]), variations in HR or HRV can be evaluated by many different methods and measures. Overall, measures of HRV can be divided into three classes: the time domain, frequency domain and non-linear. The most commonly used measures of HRV are summarized in Table 2.

3.1.1 Time Domain Measures

Time domain measures can be derived from direct measurements of the normal-to-normal intervals (NN intervals) of instantaneous HR, or from the differences between NN intervals. Within the included studies, reported time domain measures include the mean NN interval in milliseconds (ms) [53, 61, 65], the mean standard deviation (SD) of all NN intervals (SDRR or SDNN in ms [54–56, 59, 61, 65, 66]), the square root of the mean of the sum of the squares of differences between adjacent NN intervals (RMSSD) in ms [53–56, 59, 63, 65, 66], or the number of pairs of adjacent NN intervals differing by more than 50 ms divided by the total number of all NN intervals (pNN50 in % [54–56, 65, 66]) or simple NN50 count [55]. Aside from these frequently used measures, authors reported the SD of the mean of all NN intervals for 5-min segments (SDANN [56, 59, 66]) and the mean of the SD of all normal NN intervals for all 5-min segments (SDNNIDX [53, 56, 59]). Furthermore, the study by Cervantes Blásquez et al. [55] used the triangular interpolation of NN interval histogram (TINN), as described elsewhere [62].

3.1.2 Frequency Domains

Parametric and non-parametric methods to analyze the power spectral density (PSD) of HRV allow the calculation of different spectral components of short- and long-term recordings of HRV. From short-term recordings, three different main spectral components are distinguished: very-low frequency (VLF; ≤0.04 Hz), low frequency (LF; usually 0.04–0.15 Hz) and high frequency (HF; usually 0.15–0.4 Hz) components. Furthermore, an ultra-low

Table 1 Included studies by study design and authors, in alphabetical order

References	Country	Population	HRV measures taken	Main study focus	HRV/swimming related finding
Control group designs					
Franke et al. [58]	USA	Members of the Iowa State University male intercollegiate swim team ($n = 9$; mean age ± SD 20.1 ± 0.4 years) and track team ($n = 11$; mean age ± SD 21.3 ± 0.05 years); both groups were considered to be endurance-trained with the primary difference in training being the exercise modality and posture used	HF, LF, LF/HF, TP	To determine whether highly fit swimmers have greater orthostatic tolerance than equally fit runners and whether there are group differences in the autonomic responses to central hypovolemia	↑ TP in the runners than the swimmers throughout LBNP; no significant differences while SUP and resting; no significant differences after data normalization on LF or HF
Lakin et al. [61]	Canada	Healthy, young subjects ($n = 21$; M/F = 11/10[a]); UT ($n = 11$; mean age ± SD 23.0 ± 1 year); TT ($n = 10$; mean age ± SD 23.0 ± 1 year); TT: established triathletes (>2 years of training and competitive experience), or recreational triathletes performing a mixture of running, cycling and swim training (4–6 days/week, 3–4 h/week per modality, with exercise sessions, 45–90 min)	HF, LF, LF/HF, NN, SDNN	To compare the effects of intensity- and duration (30 min)-matched cycling and swimming (Swim-Cooper-Test) exercise on the post-exertional (ER, MR, LR) response in young, healthy TT and UT individuals	Swimming: UT: ↓ NN during ER and MR compared with BL; TT: ↓ NN, SDNN, HF and ↑ LF, LF/HF during ER compared with BL; ↓ NN, HF and ↑ LF, LF/HF during MR compared with BL; ↓ NN, ↑ LF/HF during ER, MR and LR compared with cycling; ↑ LF and ↓ HF compared with UT
Triposkiadis et al. [65]	Greece	Highly trained pre-pubertal swimmers ($n = 25$; M/F = 15/10; mean age ± SD 11.9 ± 1.6 years) at national and international level; controls ($n = 20$; M/F = 1/6[b]; mean age ± SD 11.3 ± 0.6 years); training sessions of 12–14 h weekly for at least 4 years	HF, LF, LF/HF, NN, pNN50, SDNN, RMSSD	To compare HRV in a group of highly trained pre-pubertal swimmers with those of active but not training children	↑ NN, SDNN, pNN50, RMSSD and HF in swimmers compared with controls; ↓ LF/HF in swimmers compared with controls
Vinet et al. [66]	France	Highly trained pre-pubertal boys, swimmers ($n = 11$; mean age ± SD 11.9 ± 0.9 years); age-matched active controls ($n = 9$; mean age ± SD 11.6 ± 1.1 years); fitness level questionnaire (i.e. sport practice, years of practice, number of hours of sports per weeks, best record in swimming competition)	HF, LF, LF/HF, TP, pNN50, SDNN, RMSSD, SDANN measures during sleep	To compare HRV parameters in highly trained swimmer boys and untrained counterparts	No statistically significant differences
Crossover designs					
Al Haddad et al. [53]	France	Highly-trained swimmers ($n = 8$; M/F = 4/4; mean age ± SD 19.6 ± 3.2 years); training ~21 h per week; two competed at an international level, others competed in the first French National League; all participated in heats for the national team selection	NN, RMSSD	To investigate the effect of daily CWI compared with a control condition, during a typical training week, on parasympathetic activity and subjective ratings of well-being	↓ RMSSD during training week in CON; ↑ RMSSD during training week in CWI; ↑ RMSSD in CWI compared with CON on days 2, 3, 4, 5; ↑ NN in CWI compared with CON on days 3, 4

Table 1 continued

References	Country	Population	HRV measures taken	Main study focus	HRV/swimming related finding
Atlaoui et al. [54]	France	French swimmers competing nationally and internationally (n = 13); males (n = 9; mean age ± SD 23 ± 4); females (n = 4; mean age ± SD 21 ± 2 years); background in competitive swimming: 15 ± 3 years; 50 m, 100 m, 200 m, 400 m, or 1500 m specialists (different strokes); trained 6 days per week, usually twice a day, practiced regular dryland training, 1 h per day	HF, LF, LF/HF, TP, pNN50, SDNN, RMSSD, SDNNIDX	To determine the relationship between HRV changes and both training variations (IT, RT) and performances in elite swimmers	HF correlated with performance during RT; at the end of RT, performances were significantly negatively related to LF/HF and LF and positively related to HF; between IT and RT periods, changes in TSF were related to the changes in HF (↑ TSF, ↑ HF), LF (↑ TSF, ↓ LF) and LF/HF (↑ TSF, ↓ LF/HF)
Cervantes Blásquez et al. [55]	Spain	Master swimmers (n = 10; M/F = 4/6; mean age ± SD 47 ± 6.81 years); members of the Masters swimming team of a Spanish private club; mean ± SD 8 ± 2.07 years participating in national competitions	HF, LF, LF/HF, VLF, NN, NN50; pNN50, SDNN, RMSSD, TINN, non-linear Poincaré analysis (SD1, SD2)	To examine how the ANS indexed by HRV regulates the heart during pre-competitive anxiety in swimmers under two different conditions (TC vs. CC)	↓ RMSSD, HF, SD1 in CC; ↑ LF/HF in CC
Chalencon et al. [56]	France	Swimmers of regional to national level (n = 10), males (n = 6; mean age ± SD 17.3 ± 2.8 years); females (n = 4; mean age ± SD 15.8 ± 1.9 years); mean ± SD intensive training history: 5.6 ± 2 years; mean ± SD training duration 10.7 ± 2.9 h per week during season	HF, LF, LF/HF, TP, pNN50, SDNN, RMSSD, SDANN, SDNNIDX	To compare the response of performance and nocturnal ANS activity to 31 weeks of training; to build a model to support a consistent relationship between ANS activity, fatigue and sports performance	Significant relationship between HF and individual performance: ↑ HF = ↑ performance
Garet et al. [59]	France	Regional-level swimmers (n = 7; M/F = 4/3; mean age ± SD 16.6 ± 0.5 years); mean ± SD history of 6.4 ± 0.9 years of practice	SDNN, RMSSD, SDANN, SDNNIDX; $HF_{wavelet}$, $LF_{wavelet}$, $VLF_{wavelet}$, $LF_{wavelet}/HF_{wavelet}$, $TP_{wavelet}$, measures during sleep	To quantify the association between changes in ANS activity and changes in three 400-m front-crawl swim performances (Perf1, Perf2, Perf3) during/at the end of three successive periods (RP1, TR, RP2) over 7 weeks	↓ SDNNIDX Perf2 compared with Perf1; ↑ SDNNIDX Perf3 compared with Perf1; positive correlation of SDNN, SDNNIDX, $HF_{wavelet}$, $TP_{wavelet}$ and performance
Parouty et al. [62]	France[c]	Well-trained swimmers (n = 10[d]; M/F = 5/5; mean age ± SD 19.0 ± 3.9 years) at national level; 24 h $week^{-1}$ training	RMSSD	The effect of CWI compared with CON on sprint swimming performance	CWI was associated with a 'likely' smaller decrease in RMSSD, with a standardized difference considered as 'moderate'
Perini et al. [63]	Italy	Swimmers (n = 9; M/F = 3/6; mean age ± SD 15.9 ± 1.55 years); involved in swimming activity at competitive level for at least 5 years	HF, LF, LF/HF, TP for SUP and ST position	To test if seasonal training is associated with changes of HRV before and at the end of the competitive season	None of the calculated parameters of HRV were significantly affected by training, no significant HRV differences at post-season compared with pre-season
Schmitt et al. [64]	France	National-level male swimmers (n = 8; mean age ± SD 17.0 ± 1.8 years); no further specification	HF, LF, LF/HF, TP for SUP and ST position	To test the hypothesis that training (17 days, twice a day) at two different altitudes (1200 m vs. 1850 m) induces specific modifications of HRV	↑ TP_{SUP}, TP_{ST}, HF_{SUP}, LF_{ST} during 1200 m altitude; change in performance between altitudes was correlated with the change in HF_{SUP}

Table 1 continued

References	Country	Population	HRV measures taken	Main study focus	HRV/swimming related finding
Other studies					
Di Michele et al. [57]	Italy	High-level swimmers ($n = 14$); males ($n = 6$; mean age ± SD 19.6 ± 3.0); females ($n = 8$; mean age ± SD 15.5 ± 6.0 years); all athletes competed at the national or international level, and most were specialized in the front-crawl style; mean ± SD training experience: male: 8.2 ± 2.6 years, female: 5.4 ± 2.3 years	HF_{POW}: $HF_{POW\text{-}RSA}$, $HF_{POW\text{-}STR}$	To assess the agreement between HRV and LA to estimate the AT in an incremental front-crawl swimming test	Overall, very good agreement between LA and HRV to estimate AT
Hellard et al. [60]	France	Elite swimmers ($n = 18$; M/F = 10/8; age: 19–30[e] years)	HF, LF, LF/HF, VLF, non-linear Poincaré analysis (SD1, SD2) for SUP and OP	To test the hypothesis that a shift in autonomic balance toward sympathetic predominance is associated with a higher risk of infection in swimmers	↑ Parasympathetic indexes assessed 1 week earlier in SUP linked to ↑ risk of URTPI and MP; same week: risk of MP in SUP linked with ↑ in sympathetic and parasympathetic and gain in LF/HF; same week: ↓ HF associated with ↑ risk of MP; ↑ AP risk in winter and for an ↑ TP associated with a decline in SD1 in SUP; OP in winter: ↓ HF week earlier ↑ risk of AP; gain in LF/HF linked to an increase in URTPI and MP; ↑ LF and ↓ SD1 in OP associated with an ↑ risk of MP

Classes of studies: (1) control group design; (2) repeated measures design; (3) other design

ANS autonomic nervous system, *AP* all-type pathologies, *AT* anaerobic threshold, *BL* baseline, *CC* competition condition, *CON* out-of-water control condition, *CWI* cold-water immersion, *ER* early recovery, *F* female subjects, *HF* high-frequency HRV, HF_{POW} high-frequency spectral power, $HF_{POW\text{-}RSA}$ high-frequency power relative to respiratory sinus arrhythmia, $HF_{POW\text{-}STR}$ high-frequency spectral power relative to the stroking modulation of heart rate, *HRV* heart rate variability, *IT* intense training, *LA* blood lactate concentration, *LBNP* lower body negative pressure, *LF/HF* low-frequency high-frequency ratio, *LF* low-frequency HRV, *LR* late recovery, *M* male subjects, *MP* muscular problems, referred to as muscle injury, pulled muscles, tendinopathies, delayed-onset muscle soreness persisting >24 h after training, shoulder-pain syndrome, and knee-pain syndrome, *MR* mid recovery, *NN* normal-to-normal intervals, *NN50* count of adjacent cycles greater than 50 ms apart, *OP* orthostatic position, *Perf x* performance number, *pNN50* percentage of adjacent cycles greater than 50 ms apart, *RMSSD* square root of the mean of the sum of the squared differences between adjacent normal RR intervals, *RP1* recovery period 1, *RP2* recovery period 2, *RT* reduced training, *SD* standard deviation, *SD1* instantaneous beat-to-beat variability, *SD2* long-term beat-to-beat variability, *SDANN* standard deviations of the mean of all normal RR intervals, *SDNN* standard deviation of all normal RR intervals, *SDNNIDX* mean of the standard deviation of all normal RR intervals for all 5-min segments, *ST* standing, *SUP* supine position, *TC* training condition, *TINN* triangular interpolation of NN intervals, *TP* total power, *TR* training period, *TSF* total score of fatigue, *TT* triathlon trained, *URTPI* upper respiratory tract and pulmonary infections, *UT* untrained, *VLF* very-low frequency HRV, *x wavelet* frequency domain measures determined by wavelet transform analysis, ↑ indicates an increase of the selected measure, ↓ indicates a decrease of the selected measure

[a] No sex ratio per group is reported

[b] The reported sex ratio by the authors probably relates to a writing error and should be 14/6

[c] Unclear where participants were recruited; country was derived from the affiliation of the first author

[d] Due to a technical failure with the HR belt in two participants, HR measures were only available in eight subjects

[e] No mean age is reported

Table 2 Frequently used HRV measures

Name	Description/definition	Unit	ANS branch
HR	Simple heart rate	BPM	
IBI	Raw duration of R-wave to R-wave intervals	ms	Mixed
Time domain measures (based on the interbeat intervals directly or on differences between successive interbeat intervals. In addition, there are both short- and long-term indices)			
NN	Normal-to-normal intervals	ms	Mixed
SDNN	Standard deviation of all NN intervals	ms	Mixed
SDANN	Standard deviation of the average of NN intervals for each 5-min period over 24 h	ms	Mixed
pNN50	Percentage of adjacent cycles that are greater than 50 ms apart	%	Primarily vagally mediated
RMSSD	Root mean square of successive differences. This index acts like a high-pass filter, thus removing long-term trends and slower-frequency variability from the signal. Because of the frequency characteristics of the autonomic influences on the heart, such that vagal influences cover the full frequency range and sympathetic influences are primarily restricted to the lower frequencies, RMSSD reflects primarily vagal influences	ms	Primarily vagally mediated
Frequency domain measures (frequency domain analysis yields information about the amount of variance or power in the heart rate or heart period time series explained by periodic oscillations at various frequencies. Power spectral analysis of the time series provides basic information on the amount of variance or power as a function of frequency)			
HF	High frequency (0.15–0.4 Hz)	ms^2	Primarily vagally mediated
LF	Low frequency (0.04–0.15 Hz)	ms^2	Baroreflex activity
VLF	Very-low frequency (0.003–0.04 Hz)	ms^2	Mixed
ULF	Ultra-low frequency (<0.003 Hz)	ms^2	Mixed
TP	Total power represents the variance of the measured signal about its mean value exactly equal to the time domain variance of the HR time series	ms^2	Mixed
Normalization	The so-called normalized scores represent the relative value of each power component in portion to the total power. In addition, the VLF or DC component is often subtracted from the total power in calculating the normalized values. The DC component is defined as the spectral components with a frequency less than 0.03 Hz	–	Mixed
LF/HF	The LF to HF ratio (LF/HF) has been proposed to reflect the sympathovagal balance. The LF to HF ratio may provide some insight into the relative relationship among autonomic influences	–	Baroreflex activity

HRV heart rate variability, *ANS* autonomic nervous system, *BPM* beats per minute, *DC* mean value of the waveform frequency component (ULF) can be derived from spectral analysis in long-term recordings (e.g. 24 h). Depending on the length of the recording, different frequency domain measures with different frequency bands (see Table 1) are reported within the included studies, including the power in HF [54–58, 60, 61, 63–66], the power in LF [54–56, 58, 60, 61, 63–66], the power in VLF [55, 60], or total power (TP) [54, 56, 58, 63, 64, 66]. Additionally, the ratio between LF and HF (LF/HF ratio) serves as another measure of HRV and is frequently included within the reviewed studies [54–56, 58, 60, 61, 63–66]. Respiratory sinus arrhythmia (RSA), the square root of the mean squared difference of successive NNs (RMSSD) and the high-frequency component of the power spectrum (HF_{POW}) are closely related and are strongly associated with cardiac vagal influence and thus represent parasympathetic activity (Table 2). On the other hand, and contrary to conventional wisdom, low-frequency HRV (LF) reflects baroreflex activity rather than sympathetic activity [67–69].

Besides these frequently used measures (Table 2), one study [57] reported a different method to analyze the HF component. The authors separated the HF_{POW} (spectral power in the HF range [0.15–2 Hz]) of each spectrum into two components. The first component included the spectral power relative to the respiratory modulation of HR ($HF_{POW\text{-}RSA}$), whereas the second component included the spectral power relative to the stroking (locomotor) modulation of HR ($HF_{POW\text{-}STR}$). Details on this approach are described elsewhere [57]. Furthermore, one study [59] reported wavelet-transformed frequency domain measures of $HF_{wavelet}$, $LF_{wavelet}$, $VLF_{wavelet}$, $LF_{wavelet}/HF_{wavelet}$, and $TP_{wavelet}$. In case of HRV analysis, the wavelet transform analysis is devoted to the extraction of characteristic frequencies, contained along a signal of consecutive NN intervals. The analysis amounts to sliding a window of different weights (corresponding to different levels) containing the wavelet function, all along the signal, as further described by the authors [59].

3.1.3 Non-Linear Measures

Two of the included studies [55, 60] used non-linear Poincaré analysis to calculate indices of HRV. The Poincaré method consists of plotting the length of each NN interval against the length of the previous NN interval. Both studies [55, 60] used two standard Poincaré plot descriptors: the SD1 is a measure of instantaneous variability (successive beats) and is taken as an indicator of parasympathetic activity, whereas the SD2 represents long-term variability and indicates both parasympathetic and sympathetic activities.

3.2 Nature of Included Studies

The included studies broadly fell into three classes: (1) studies using a control group design to compare HRV in swimmers with subjects allocated to a control group (e.g. non-swimmers, runners); (2) interventional studies measuring HRV over training progress (e.g. relating HRV to performance measures in swimmers), measuring HRV to address different modalities of training (e.g. differences in altitude, intense vs. reduced training) or recovery (i.e. cold-water immersion [CWI]) within a repeated measures design; and (3) other studies using HRV to address a specific problem (e.g. association of HRV and risk of infection in swimmers, pre-competitive anxiety in swimmers, HRV to estimate anaerobic threshold (AT)—mostly correlation studies).

3.2.1 Control Group Designs: Differences in the Autonomic Nervous System Function

Three studies investigated differences in ANS function indexed by HRV in swimmers compared with a control group (control group design). Of these, two studies investigated differences in HRV in highly trained pre-pubertal swimmers compared with untrained counterparts. The earlier study by Triposkiadis et al. [65] found a predominance of vagal tone in prepubertal swimmers. All parameters of HRV that are strongly dependent on parasympathetic activity—both in the time domain and the frequency domain measures (Table 2)—were significantly increased in prepubertal swimmers compared with controls (Table 1). The later study by Vinet et al. [66] reported no significant differences between groups (swimmers vs. untrained boys) for all frequency domain measures independent of the mode of expression (absolute in ms^2, relative in ln or %) and time domain measures. The authors mentioned that their results demonstrated that participating intensively in swimming training does not induce changes in HRV indices. Regarding the controversial nature of their results compared with Triposkiadis et al. [65], Vinet et al. [66] argue that differences between the two studies could be explained by the population studied (boys and girls vs. boys; training volume: 12–14 h per week vs. 8–10 h per week) and different methods of quantifying HRV.

The study by Franke et al. [58] also focused on differences in ANS function by determining whether highly fit swimmers have greater orthostatic tolerance in comparison to equally fit runners, and whether there are group differences in the autonomic responses to central hypovolemia. However, the authors summarized that neither orthostatic tolerance nor HRV responses to graded lower body negative pressure (LBNP) within a testing chamber differed between the runners and swimmers, suggesting that differences between run and swim training do not affect these responses.

Lakin et al. [61] compared the effects of intensity- and duration-matched cycling and swimming exercise on the post-exertional early-, mid- and late-recovery response in young, healthy, triathlon trained (TT) and untrained (UT) individuals. In the UT group, there were no significant differences in indices of ANS function between the cycling and swimming exercise group. However, the TT group demonstrated a significant increase in LF and decrease in HF at early- and mid-recovery compared with pre-exercise following swimming, and increase in the LF/HF compared with baseline and cycling exercise after swimming, indicating a slower recovery of these indices following swimming [61]. No differences between the groups were observed following cycling exercise. Following swimming, significant group differences during early- and mid-recovery were present. The authors suggested that HRV response to exercise is dependent on both training status and exercise modality [61].

Of these higher class (i.e. better-designed, controlled) studies, two showed significant differences between the groups studied, while two other studies did not reveal any difference in ANS function or reactivity, as indexed by HRV, between groups. One study revealed a predominance of vagal tone in highly trained pre-pubertal swimmers compared with untrained counterparts [65], while a later study with a similar research question and design [66] failed to replicate these findings. One study [61] found differences in the post-exertional recovery response in triathlon-trained subjects compared with untrained individuals after swimming, while another study [58] was not able to report differences in highly fit swimmers compared with equally fit runners in the autonomic responses to central hypovolemia.

3.2.2 Crossover Designs: Variations in Training, Task or Recovery Modalities

The majority of studies used a repeated measures design for the evaluation of variations within the experimental protocol and their comparative effects on HRV. These variations addressed different training intensities (intense training vs. reduced training, Atlaoui et al. [55]), different conditions (training condition vs. competition condition, Cervantes Blásquez et al. [55]; intensive training vs. taper recovery periods, Chalencon et al. [56]; resting period vs. training period, Garet et al. [59]), different times of the season (before vs. at the end of the competitive season, Perini et al. [63]), different training locations (altitude: 1,200 vs. 1,850 m, Schmitt et al. [64]), or different recovery modalities (CWI, Al Haddad et al. [53, 63] and Perini et al. [53, 63]).

Three studies [54, 56, 59] showed that HR was significantly related to swimming performance. In particular, greater HF power—representing parasympathetic activity—was significantly associated with greater performance [54]. However, one study [59] assessed measurements of HRV and autonomic function while participants were asleep, which is not comparable with the other two studies [54, 56].

The study by Atlaoui et al. [54] measured HRV in competing national and international swimmers over a 7-week period. The swimmers were tested before and after a 4-week intense training period (IT) and a 3-week reduced training period (RT). At the end of each period, the swimmers performed in a competition and answered a questionnaire on fatigue. The authors found that HF HRV correlated with performance both during and at the end of RT, i.e. performances were significantly negatively related to LF HRV and LF/HF ratio, and positively related to HF. Furthermore, the authors found changes in fatigue positively related to changes in HF and negatively related to LF and LF/HF ratio between the IT and RT periods. The authors summarized their findings that HF, LF and LF/HF are significantly related to swimming performance, and those swimmers with higher HF and lower LF/HF, after the 3 weeks of RT, reported lower fatigue [54]. However, no significant changes in HRV with training load variations were found. The authors concluded that in highly trained swimmers who coped well with their training program, higher levels of HF during taper constituted a favorable condition to increased swimming performance, and that HRV changes during that time are a valuable tool for monitoring the adaptation in variations of training load and, hence, to improve performance in elite swimmers during periods of reduced training.

Garet et al. [59] aimed to quantify the association between changes in night-time ANS activity and changes in three 400-m front-crawl swim performances during or at the end of three successive periods of recovery or training over 7 weeks. The training load of the swimmers was reduced between the intensive training period (following a first recovery period) and the recovery periods. While no differences in mean performance between the three assessments were found, mean SDNNIDX showed a quadratic trend, such that there was a decrease in performance from 1 to 2, and a rise back to baseline in performance 3. The authors reported various trends for wavelet transform indices of TP and HF—that are associated with global and parasympathetic activity—and wavelet transform indices of LF, but did not report on the significance of effects [59]. However, when individual data was plotted against associated changes in performance, TP ($TP_{wavelet}$) showed a significant positive correlation. Furthermore, other correlations with time (i.e. SDNNIDX) and frequency measures associated with global and parasympathetic activity were significant but weaker. The authors concluded that individual relative variations in performance and individual relative variations in nocturnal ANS activity are closely related [59].

Chalencon et al. [56] observed swimmers of regional to national level over 31 weeks at two cycles of intensive training and taper recovery periods to compare the response of performance in weekly morning 400-m freestyle time trials and nocturnal ANS activity. The authors found a logarithmic relationship between performance and ANS activity, where higher HF was associated with greater performance. The authors concluded that their results demonstrated the relevance of HRV measurement as a valuable tool to assess physiological training-induced responses and to optimize athletic performance [56].

Cervantes Blásquez et al. [55] addressed differences of pre-competitive anxiety and HRV in swimmers under a training condition (TC) and a competition condition (CC), and found HRV related to pre-competitive anxiety under different conditions. Pre-competitive anxiety scores for somatic anxiety on the Competitive State Anxiety Inventory-2 (CSAI-2) were higher in the CC than the TC. The authors noticed a significant decrease in the RMSSD, whereas all other time domain measures of HRV showed no significant differences between the conditions. Nonlinear HRV analysis revealed that SD1 was significantly lower during CC. Furthermore, there was a significant increase of the LF/HF ratio and a decrease of HF in the CC. All parameters that increased their value significantly in the CC were related to sympathetic activity and all parameters that decreased significantly were related to parasympathetic activity. Overall, the authors provided evidence for a change in autonomic control in competitive situations and in the presence of pre-competitive anxiety [55].

Another study [63] showed that improvement in physical fitness observed from the beginning to the end of the athletes' competitive season was associated with decreased HR and BP at rest, but with no change in the corresponding vagal and sympathetic spectral markers indexed by HRV. The authors found significant differences on various HRV measures in the supine and sitting position, but no significant HRV differences at post-season compared with the pre-season were observed. The authors concluded that the improvement in physical fitness observed from the beginning to the end of the athletes' competitive season was associated with decreased HR and BP values at rest, but with no change in the corresponding vagal and sympathetic spectral markers indexed by HRV [63].

Significant effects of the altitude of the training location on HRV were revealed in another study [52]. During training at an altitude of 1200 m, various HRV indices increased. However, none of these parameters changed during training at an altitude of 1,850 m; nevertheless, swimming performance improved. Again, and this deserves special notice, the authors found the change in performance was correlated with an increase in vagal activity, as indexed by HF HRV. The authors tested the hypothesis that 17 days of training (twice a day) at two different altitudes (1,200 vs. 1,850 m) induces specific modifications of HRV. They observed a difference in HRV changes between the two altitudes. During training at an altitude of 1,200 m, supine and standing TP and supine HF, as well as standing LF, were increased. Furthermore, the 2,000-m freestyle performance was improved, whereas none of these parameters changed during training at an altitude of 1,850 m. Most interestingly, the change in performance was correlated with an increase in supine HF. The authors noted that HRV analysis in altitude appears to be a promising method for monitoring the interacting effects of hypoxia and training loads as high training loads and hypoxic stress may have cumulative effects on HRV by decreasing spectral power [64]. Their results are in line with the study by Chalencon et al. [56] who found a logarithmic relationship between performance and ANS activity, where higher HF was associated with greater performance. Based on the evidence from these studies, one may generally conclude that greater HRV, especially HF, is associated with better swim performance.

Furthermore, two studies investigated the effect of CWI [62] or daily CWI [53] as recovery intervention for swimmers. While one study found that the intervention resulted in slower swimming times and a smaller decrease in RMSSD [62], the other study [53] found that daily intervention following training was associated with greater resting cardiac parasympathetic activity indexed by RMSSD. Parouty et al. [62] investigated the effect of CWI compared with an out-of-water control condition on sprint swimming performance in well-trained swimmers who were randomly assigned to a specified sequence of conditions. Each participant completed both conditions on two testing sessions at the same time of day, 6–7 days apart. CWI was associated with a decrease in swimming performance and a smaller decrease in RMSSD after the first of two 100-m swimming sprints. The authors concluded that, despite a subjective perception of improved recovery following CWI, the intervention resulted in slower swimming times and therefore is unlikely to provide any performance benefit to well-trained swimmers [62]. In a similar study design, Al Haddad et al. [53] investigated the effect of daily CWI compared with a control condition where subjects rested seated without immersion, during a typical training week, on parasympathetic activity and subjective ratings of well-being in a randomized crossover design. The authors found that daily CWI recovery following training was associated with greater resting cardiac parasympathetic activity—indexed by RMSSD—and a better maintenance of perceived sleep quality throughout the training week. As direct benefits of CWI on physical performance and training adaptation warrants further investigations, the authors concluded that future studies investigating the influence of other immersion modalities on subjective ratings, ANS activity, training adaptation and performance are needed [53].

3.2.3 Other Studies

Two other studies with different study designs to those described above were included in the systematic review. Di Michele et al. [57] assessed the relationship between HRV and lactate concentration (LA) to estimate the AT in an incremental front-crawl swimming test in high-level swimmers. The authors found an overall strong relationship between LA and HRV to estimate AT. They concluded that it is possible to estimate the AT from the HRV in an incremental front-crawl swimming test and that the strong agreement between the HRV threshold and the LA_{AT} supports the possibility of using the HRV-based method for the actual testing of swimmers [57].

Hellard et al. [60] tested the hypothesis that a shift in autonomic balance toward sympathetic predominance is associated with a higher risk of infection in swimmers. They observed 18 elite swimmers over the time course of 2 years in two Olympic preparation centers. Symptoms and HRV were measured on a weekly basis, with eight HRV variables quantified in the supine and orthostatic positions. The authors found that an increase in parasympathetic indexes in the supine position assessed 1 week earlier was linked to a higher risk of upper respiratory tract and pulmonary infections (URTPI) and muscular problems (MP; muscle injury, pulled muscles, tendinopathies, delayed-onset muscle soreness persisting >24 h after training, shoulder-pain syndrome, and knee-pain syndrome) [60]. During the same week of measurement and symptom documentation, a higher risk of MP was linked with an increase in sympathetic and parasympathetic indices and a gain in the LF/HF. Measured in the orthostatic position, a decrease in HF was associated with an increased risk of MP measured during the same week, and a gain in the LF/HF ratio was statistically linked to an increase in URTPI and MP. Furthermore, increased LF and decreased SD1 in the OR position were associated with an increased risk of MP, and an increase in the TP of HRV associated with a decline in SD1 in the supine position was associated with a higher risk for all-type pathologies in winter. The authors summarized their findings and noted that the weeks that preceded the appearance of URTPI and MP were characterized by an increase in autonomic parasympathetic activity in the supine position. Therefore, the authors concluded that HRV is a rapid and non-invasive tool to indicate autonomic function, which provides complementary information that may help to reduce the risk of infection in elite swimmers [60].

4 Discussion

The present systematic review aimed to summarize trends in the use of HRV measurements in the field of swimming research. A search of three prominent electronic databases by defined search strategies (see ESM Appendix), according to the PRISMA statement, revealed 194 total studies (after removing duplicates). Abstracts were then screened for eligibility for inclusion within the review under predefined inclusion criteria. An extensive search strategy of three major databases was applied. However, the review is still limited as one full text was not retrieved and several conference proceedings were not included. Fourteen studies meeting the inclusion criteria were included within the review. Besides one study from the US and one from Canada, all studies were conducted in Europe, with studies coming from France ($n = 8$), Italy ($n = 2$), Greece ($n = 1$), and Spain ($n = 1$). All included studies were published after the year 2000, with nine studies published between 2000 and 2012, and six studies published within the last 3 years. The first guideline [52] on standards of measurements, physiological interpretation and clinical use of HRV was published in 1996 and, thus, only studies published after 1996 were included in the review. Included studies therefore show a general good reporting of HRV methods applied and measures derived. Most studies reported the frequently used measures of HRV that are summarized in Table 2. However, differences in the methods of HRV recording carry a potential bias when comparing results from different laboratories that use different devices to record HRV or different algorithms for its analysis. Furthermore, measuring HRV during swimming, or shortly after exercise, comes with several methodological challenges. Most studies used ambulatory devices such as the s810 [53, 54, 56, 59, 60, 62, 63], or the S810i [55, 57] (Polar Electro, Kempele, Finland). Although these Polar recorders have been reported as reliable and valid tools when compared with an ECG [70, 71], and are more practical in such applied situations due to the affordability of the device [72], if possible, traditional ECGs should be used for both gathering and editing of HRV data [73]. Furthermore, as thermoregulation is driven by the ANS, HRV measurements are affected by changes in the environmental temperature [74, 75] that might occur by transition of athletes wearing only swim clothes into or out of the water. While some authors' demonstrated possible ways to control for core and skin temperature [61] in study designs that required HRV assessment shortly after or during exercise, the general influence of environmental factors in this particular field of research appears to have been underestimated.

Studies reviewed in this article fell mainly into three classes; control group designs [58, 61, 65, 66] to investigate between-subject differences (i.e. swimmers vs. non-swimmers, swimmers vs. other athletes); repeated measures designs [53–56, 59, 62–64] on within-subject differences of interventional studies measuring HRV to address different modalities of training or recovery; and other studies not falling into one of the aforementioned classes of studies—using HRV to address a specific problem such as the association of HRV and risk of infection in swimmers.

The controversial results from control group designs on differences in the ANS function between trained and untrained subjects [65 vs. 66, 58 vs. 61] are probably driven by methodological aspects that are crucial and should always be taken into account when interpreting and comparing HRV data from different studies. For example, the studies by Triposkiadis et al. [65] and Vinet et al. [66] not only differed in sample size ($n = 25/20$ vs. $n = 11/9$) and sex ratio (boys and girls vs. boys) but also on length of HRV recording (512 RR intervals vs. 6 min of a total of 4 h of recordings), the condition of recording (at rest vs. during sleep) and the technical device used (12-lead ECG vs. portable holter monitoring). Differences in the studies by Franke et al. [58] and Lakin et al. [61] might also result from different sample sizes ($n = 9/11$ vs. 21/10), sex ratios (only male vs. balanced), length of HRV recording (256 RR intervals vs. 5 min), the condition of recording (supine vs. seated position), and the technical device used (5-lead vs. 3-lead ECG). While some of these results are therefore controversial, they reveal that investigating HRV differences between (1) trained and untrained individuals or (2) different types of athletes, and by (3) task and/or (4) training modality are fields of interest for future studies.

Crossover designs with repeated measures foremost focused on the improvement of training modalities for professional swimmers. From this class of included studies one can generally state that HRV seems to be related to swimming performance. Of particular interest for future studies is the investigation of (1) the specific role of parasympathetic activity indexed by time (i.e. RMSSD, pNN50) and frequency domain measures (i.e. HF) of HRV—as most studies revealed a significant correlation of performance measures with these parameters of HRV; (2) the effect of recovery interventions on the ANS that can be assessed using measures of HRV; and (3) to explore to what extent HRV can mirror the impact of different training modalities. The particular association of swim training and vagal activity is in line with findings from research on animals. Recent research in rats suggests that resting bradycardia (induced by swim training) is mainly mediated by parasympathetic activity and differs from other training modes (i.e. running) that seem to decrease intrinsic HR [76]. Future studies in humans should emphasize this particular association and investigate the differences between swimming and other modalities of physical activity. However, since numerous factors influence autonomic modulation of the HR (e.g. age, time of the day, nutrition) and thus affect experimental data, caution should be used in implying causation in the results of studies, which are largely based on correlation data. Prospective trials and well-controlled replication studies are necessary to strengthen the existing evidence on a possible relation between HRV and swimming performance.

Besides the studies summarized with control group and crossover designs, two other studies were included in the systematic review. One [57] assessed the agreement between HRV and LA to estimate the AT in swimmers and found that it is possible to estimate the AT from the HRV. Recently, several studies aimed to develop methods for estimating the AT [77] from HRV [78, 79]. HRV allows the differentiation of sub- from supra-ventilatory-threshold exercise [79], and oxygen consumption at the ventilation AT level was related to the variance of RR intervals [78]. However, given the large variability in both measures, the feasibility of such applications needs to be questioned. It has been shown that combined methods are superior (over the use of a single method) and more accurate in the determination of ventilatory thresholds. Based on the evidence reviewed, this should also be taken into account when using HRV to determine ventilatory threshold. The other study [60] found that changes in HRV are associated with the risk of infection in swimmers, and provides information that may help to reduce the risk of infection in elite swimmers. These types of studies promote the integration of the use of HRV measures in regular training in professional athletes, and the latter study points to the prospective value of HRV assessment. While clinical research emphasizes the prognostic or predictive value of HRV [80–84], the study by Hellard et al. [60] was the only one treating HRV as independent variable to predict the risk of infection. The utility of HRV to determine individual training load or expected performance outcome by a priori baseline assessment might further be of interest in the development of new fields of research.

5 Conclusion

The assessment of ANS activity underlying physical activity is of interest for professionals in the field of sports to improve training processes and competitive outcomes.

Of particular interest seems the appropriate assessment of parasympathetic activity, as recent research suggests that a high and relatively stable vagal activity during preparation may indicate a readiness to train or appropriate recovery that positively affects performance in athletes [85]. Furthermore, measures of training-induced disturbances in autonomic control may provide useful information for training prescription [86]. HRV provides a feasible, non-invasive measurement for the quantification of ANS activity and allows the distinct evaluation of vagal activity by different time and frequency domain measures (Table 2). Therefore, HRV has several advantages compared with other measures of cardiovascular activity during exercise.

However, studies on cardiac variability in athletes are still an almost unexplored domain [35]. While recommendations for the standardization of measurement conditions in future studies on athletes that also apply for swimmers are given elsewhere [35], this review provides a summary of the current evidence from HRV research on swimming and recommendations for future directions. Besides studies that focus on the outcome and effects of frequent swimming on ANS function, especially in adolescents, the majority of studies included in this review used measures of HRV to mirror and improve training or competition conditions and performance outcome in professional athletes. With respect to these studies, the review revealed two major findings: (1) performance in professional swimmers is correlated with ANS activity indexed by HRV (particularly parasympathetic activity); and (2) differences in training and recovery modalities can be illustrated by methods of HRV measurement and analysis.

While the feasibility and possibilities of HRV measures for this particular field of application are well documented within the existing literature, it seems that their incorporation in regular everyday training is far from realized because HRV research on swimming faces several methodological challenges related to the particular nature of the sporting activity. Existing studies encourage the use of HRV measures for a broad variety of applications by trainers, athletes and experts within the field but more research is needed, focusing on translational approaches that transfer current evidence into regular practice.

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