Individual Interdependence between Nocturnal ANS Activity and Performance in Swimmers

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ABSTRACT

GARET, M., N. TOURNAIRE, F. ROCHE, R. LAURENT, J. R. LACOUR, J. C. BARTHÉLÉMY, and V. PICHOT. Individual Interdependence between Nocturnal ANS Activity and Performance in Swimmers. *Med. Sci. Sports Exerc.*, Vol. 36, No. 12, pp. 2112–2118, 2004. **Purpose:** Variations in autonomic nervous system activity (ANS) and variations in performances have been shown to be correlated at the group level in swimmers. The aim of the study was to investigate the strength of that relationship at the individual level. **Methods:** Seven regional-level swimmers (four male, age 16.6 ± 05 yr, 6.4 ± 0.9 yr of practice) were included in the study. They performed maximal aerobic performance on a 400-m freestyle race before and after a 3-wk intensive training period, and following a 2-wk tapering period. ANS activity was assessed through heart rate variability (HRV) indices measured the night before each race and twice a week along the protocol. **Results:** All HRV indices were altered, with global and parasympathetic indices decreasing from W1 to W3 in the whole group, while they increased until W5 in five swimmers, and continuously decreased in two. Best performances were respectively realized when global and parasympathetic indices of HRV were highest. Importantly, the relationship between the changes in performances and the changes in HRV indices was strong ($\Delta\text{Perf} = -1.232$ to $1.625 \cdot \Delta\text{HF}_{\text{wavelet}}$, $R^2 = 0.5$); the greater the rebound in ANS activity after W3, the greater the performance improvement, and reciprocally. **Conclusion:** Performance is correlated with nocturnal ANS activity at an individual level. The decrease in ANS activity during intensive training is correlated with the loss in performance, and the rebound in ANS activity during tapering tracks with the gain in performance. Interestingly, the speed of the rebound during the tapering period was quite different between swimmers. ANS activity measurement may be useful to design and control individual training periods and to optimize the duration of tapering. **Key Words:** AUTONOMIC NERVOUS SYSTEM, TRAINING, SWIMMING, SUPERCOMPENSATION, WAVELET TRANSFORM

Physical training cycles most often include periods of intensive training followed by a period of recovery. The recovery period is needed for supercompensation aims, which is related to better performances. The issues today are to optimize the load during the intensive physical training period as well as the duration of the training and the recovery period at an individual level.

Following a single bout of exercise, autonomic nervous system (ANS) activity is decreased for up to 2 d (12). During the recovery, ANS activity increases, eventually presenting a rebound with higher values than those measured before the exercise session. This pattern has been shown for isolated exercise sessions (12) as well as cumulated exercise sessions, where ANS activity decreases progressively until a period of recovery allows supercompensation (23,24,26,30).

The associations between training load and ANS activity and between performance and ANS activity seem highly individual (29). Hedelin observed that within a group, the same training load affected ANS activity in a very individual manner with participants who responded well to the training load and others slightly overtrained (14). These individual adaptations to training load seem to depend on the baseline average level of ANS activity, as quantified using HRV, that may predict responsiveness to changes in training load (13).

Decreased ANS activity has been associated with a decrease in performance and the following rebound to an increase in performance. These variations in autonomic activity and performances are strongly correlated in cross-sectional studies (17), as well as in longitudinal studies using cohorts of young (14,16,26,29) and older (24) adults and patients with chronic diseases (8,15).

Both the parasympathetic and orthosympathetic nervous systems' activities individually contribute to global ANS

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activity modifications. Their isolated short- and long-term modifications have been correlated with changes in physical performance in such a way that they constitute bases of overtraining theories (11,19,20), and may contribute in the evolution of both central and peripheral aerobic work capacities (13,27). Results are still controversial, with isolated parasympathetic and sympathetic activities being associated with performance, depending on the analysis method, the recording time, the type of sport, the type of training, and the initial level of the athlete. Portier did not report any relationship between autonomic balance changes in response to training and performance. However, Knöpfli reported an association between morning values of norepinephrine excretion and performance (16), whereas Hedelin reported an association between a gain in daytime parasympathetic activity and a gain in maximal aerobic work capacity (13). Still, at the individual level, the strength of the relationship between the amplitude of ANS indices modification and the corresponding variations in performance has never been established during a training cycle.

The purpose of this study was to quantify the association between individual changes in ANS activity and changes in performance during a period of intensive training followed by a period of tapering in a group of seven young elite swimmers.

METHODS

Subjects. A group of seven regional-level swimmers (four male, three female, age 16.6 ± 0.5 yr) participated in the study. Their height (169.3 ± 5.9 cm), weight (59.3 ± 6.5 kg), Tanner stages for puberty rating (S4), and body mass index (20.7 ± 1.5 kg·m^{-2}) were similar for all. They had a history of 6.4 ± 0.9 yr of practice, and were swimming 9 h·wk^{-1} at the time of the study. None of the subjects reported any known pathology or current medication use. A written informed consent was obtained from the subjects and their parents. The study was approved by the institution's ethical committee.

Training protocol. The protocol (Fig. 1) consisted of three successive periods: 2 wk of recovery (RP1, W0 to W1), 3 wk of intensive training period (TR, W1 to W3), and 2 wk of recovery (RP2, W4 to W5).

During the training period, the training load consisted of six 1.5-h practices per week. A significant reduction in training load was observed during the recovery period, while the swimmers continued to practice regularly (Fig. 1). Weekly training load was assessed as the product of the distance multiplied by an intensity coefficient adjusted for each training set; this was proposed by the French Swimming Federation (10) and corrected for perceived exertion (9,31). All participants reported stable daily activities besides the practice sessions, as monitored through their activity logs, without any meaningful additional workload.

Performance. Performance was the time achieved on 400-m front-crawl swims. The first was assessed in competition settings during the first recovery period (Perf 1), the second in "competition-like" training settings at the end of the heavy training period (Perf 2), and the third again in competition settings at the end of the second recovery period (Perf 3). Stroke rate, distance per stroke (28), perceived exertion, and heart rate were measured on each of these performance assessments.

Autonomic nervous system activity assessment. ANS activity was measured through heart rate variability (HRV) indices averaged on six consecutive hours of sleep where heart rate was the lowest. Recordings were performed with Polar S-810 monitors (21). Within the recordings, erroneous signals were removed using the error correction function in the Polar® software. An eventual second correction with the software MatLab® was performed as each RR interval was visually validated. Only normal-to-normal beats were considered for analysis, with intervals excluded due to artifact being replaced by holding the previous coupling interval level throughout the time interval to the next valid coupling interval. ANS activity was measured once the night before the first competition as a baseline measurement (HRV_{base}), following a week of rest (easy swim). It was thereafter measured twice a week (W1 to W5), on Tuesday and Friday nights, and each weekly result was calculated as the average of these two measurements (HRV_{W1} to HRV_{W5}). HRV analysis was performed with the software MatLab®, using the method developed by Pichot et al. (25).

Time domain analysis. On each recording, we calculated the following indices of HRV: the percentage of differences between adjacent normal RR intervals more than 50 ms (PNN50, short-term HRV); the standard deviation of all normal RR intervals (SDNN, global HRV); the square root of the mean of the sum of the squared differences between adjacent normal RR intervals (RMSSD, short-term HRV); the standard deviations of the mean of all normal RR intervals for 5-min segments (SDANN, long-term HRV); and the mean of the standard deviation of all normal RR intervals for all 5-min segments (SDNNIDX, global HRV).

Wavelet transform analysis. This analysis is devoted to the extraction of characteristic frequencies, contained along a signal that, in this case, was composed of consecutive intervals between RR interval series (1,12,25). The decomposition of a signal by wavelet transform requires a ψ

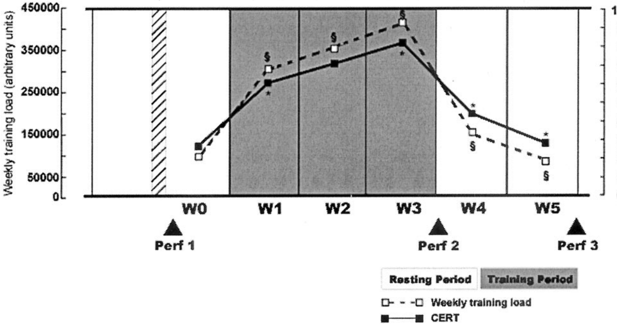


FIGURE 1—Timing of measurements, mean weekly training loads, and perceived exertion for the whole group ($N = 7$).

function adequately regular and localized, named Mother function. Starting from this initial function, a family of functions is built by dilatation and translocation, which constitutes the so-called wavelet frame. The analysis amounts to sliding a window of different weights (corresponding to different levels) containing the wavelet function, all along the signal.

In our analysis, we used the Daubechies 4 wavelet transform. For each record, the wavelet coefficients were calculated on sets of 256-RR intervals, giving seven separate levels of analysis named 2, 4, 8, ..., 128. Then we calculated the variability power, level by level, as the sum of squares of the coefficients.

Wavelet indices include the sum of wavelet power coefficients at levels 2, 4, and 8, associated with an index of parasympathetic activity; wavelet power coefficients at levels 16 and 32 ($LF_{wavelet}$), roughly representing both parasympathetic and sympathetic activities; wavelet power coefficients at levels 64 and 128 ($VLF_{wavelet}$); and the ratio $LF_{wavelet}/HF_{wavelet}$, representing an evaluation of the autonomic nervous system balance (sympathetic/parasympathetic). The low- and high-frequency indices can also be calculated in normalized units, ($LF_{wavelet}nu$ and $HF_{wavelet}nu$) as $100 \cdot LF_{wavelet}$ /(total power $-$ $VLF_{wavelet}$) and $100 \cdot HF_{wavelet}$/(total power $-$ $VLF_{wavelet}$), respectively. The total frequency power was calculated as well ($Ptot_{wavelet}$).

Statistical analysis. Each subject was its own control, the 100% reference measurement being the value calculated on the first recording (HRV_{base}). All the parameters recorded thereafter were expressed as a percentage of that reference value.

The normality of the distribution was tested with the Kolmogorov-Smirnoff normality test. Data for group analysis were compared using a two-factor ANOVA, weeks and subjects. Individual simple regression analyses were performed to assess the relationship between HRV indices and performance. Relationships between variations in HRV indices and variations in swimming performances were assessed with simple regression analyses. Results were presented as means ± standard deviations (mean ± SD). They were considered significant for $P < 0.05$.

RESULTS

Training load and perceived exertion. Training load was reduced by 69% between the intensive training period and the recovery periods ($P < 0.01$). When compared with the baseline week, weekly training loads (Fig. 1) increased significantly during the 3 wk of intensified training (all $P < 0.02$), and decreased significantly during the last 2 wk of recovery (both $P < 0.0001$).

When compared to the baseline week, mean perceived exertion increased significantly along the training period (all $P < 0.05$ but between W1 and W2, where P = NS), and decreased significantly during the RP2 (all $P < 0.05$). Individual profiles followed the same tendencies.

Heart rate, perceived exertion. A maximal effort was reached in all races (Table 1). Heart rate was within 10% of the theoretical maximal heart rate (2), and perceived exertion ranged from 7 to 10 at the end of all three 400-m front-crawl swims (HR_{max} and CERT, all NS).

The median nocturnal heart rate did not change significantly from one week to another at the group level (all NS). However, there was a tendency towards an increase from 55.7 ± 3.3 bpm at baseline to 58.6 ± 10.1 bpm at W3, followed by a decrease to 56.4 ± 9.2 bpm at W5. Large variations in heart rate modifications were observed at an individual level (from 49.2 to 60.2 bpm at baseline, from 46.1 to 71.7 bpm at W3, and from 47.6 to 75.0 bpm at W5).

Performances. No differences in mean performance were found between the three assessments (all NS, Table 1). However, individual variations in performances were fairly wide, with variations ranging from +18 s to −10 s between any two performances. Stroke frequency and distance per stroke were fairly regular within individuals, without any significant difference at the group level (all comparisons NS), and perceived exertion was maximal.

Autonomic nervous system indices, time domain. At the group level, HRV indices associated with global and parasympathetic activity decreased during TR, and increased during RP2 (Table 1), performances following the same trend. At the individual level, the evolution, the amplitude of variation, and the speed of modification of the HRV indices were highly individual. Interestingly, individual best and worst performances on 400-m freestyle swims were respectively realized when indices associated with

TABLE 1. Perceived exertion, performance, criteria and selected time-domain indices of HRV of the seven swimmers.

	Perf 1					Perf 2					Perf 3				
	Time	CERT	HR	SDNN	SDNNIDX	Time	CERT	HR	SDNN	SDNNIDX	Time	CERT	HR	SDNN	SDNNIDX
S_1	286	9.0	190	100	100	283	8.0	190	98	93	282	9.0	191	105	126
S_2	315	8.0	187	100	100	316	9.0	189	94	89	322	9.0	192	91	79
S_3	338	8.0	193	100	100	343	9.0	190	100	90	331	10.0	194	102	103
S_4	328	8.0	176	100	100	328	9.0	176	51	78	321	8.0	181	96	156
S_5	303	7.0	182	100	100	311	9.0	184	61	52	293	10.0	185	123	109
S_6	279	7.0	185	100	100	285	8.0	188	39	59	283	9.0	184	58	87
S_7	334	9.0	191	100	100	337	9.0	187	99	59	330	9.0	189	104	87
Mean	311.9	8.0	186	100	100	314.4	8.7	186	82	78*	309.4	9.1	188	101	107*
SD	23.3	0.8	6	0	0	24.2	0.5	5	31	16	22.0	0.7	5	21	27

S, subjects; Perf, performance; CERT, children effort rating table (perceived exertion); HR, heart rate; SD, standard deviation. Time is expressed in seconds (s), HR in beats per minute (bpm), time-domain indices in percentage of Perf 1 measurements (%).
* $P < 0.05$.

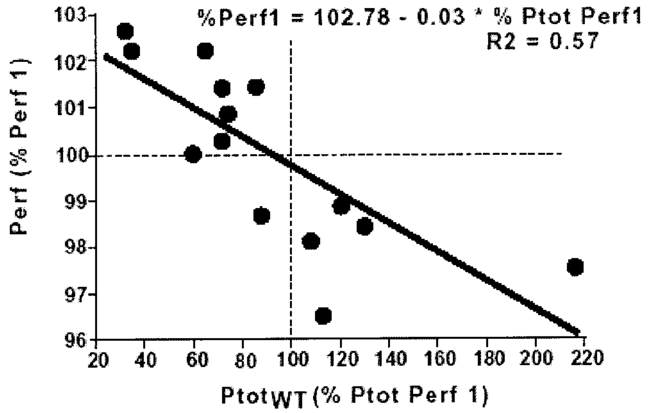


FIGURE 2—Simple regression between wavelet transform total power spectrum (Ptot$_{wavelets}$) and performance, as expressed in percentage of Perf 1 values (% time).

global and parasympathetic ANS activity (SDNN, SDNNIDX, RMSSD, pNN50) were highest and lowest, the amplitude of modification being correlated with the amplitude of increase or decrease in performance (Fig. 2, Fig. 3).

Autonomic nervous system indices, wavelet transform analysis. At the group level, wavelet transform indices associated with global and parasympathetic activity (Ptot$_{wavelet}$, HF$_{wavelet}$, HF$_{wavelet}$nu) decreased during TR and increased during RP^2 (P = NS, Table 2). This is notably the case for Ptot$_{wavelet}$: 68 ± 29% (range 32%–118%) of baseline assessment after TR, and 112 ± 50% (range 64%–216%) of baseline assessment after RP2 (all NS). Wavelet transform indices associated with sympathetic activity (LF$_{wavelet}$, LF$_{wavelet}$nu) and to the global equilibrium (LF$_{wavelet}$/HF$_{wavelet}$) followed various trends (Table 2). At an individual level, the amplitude of variation and the speed of modification of the wavelet transform indices were highly individual, as presented in the accompanying figure of Table 2 for Ptot$_{wavelet}$.

Correlations between autonomic indices and performances. The individual modifications observed for the group were widely scattered. However, when these individual data were plotted against associated changes in performance, a clear relationship appeared as for Ptot$_{wavelet}$ ($R^2 = 0.57$, $P < 0.0001$, Fig. 2). Furthermore, the relationships between changes in performance and changes in HRV indices were strong (Fig. 3), with both performance improvement and decline from baseline tracked by corresponding changes in ANS activity. The strongest correlations observed were for ΔPtot$_{wavelet}$ in the frequency domain ($R^2 = 0.54$) and for ΔSDNNIDX from the time domain ($R^2 = 0.54$). Other correlations with time and frequency indices associated with global and parasympathetic activity were significant, but weaker. Residual calculation demonstrated that 55% of the errors were within 2 s (0.64% of mean performance time).

DISCUSSION

This study reports a strong relationship between individual relative variation in performance and individual relative variation in nocturnal activity of the autonomic nervous system activity (using HRV). Within individuals, changes in ANS activity are strongly correlated with changes in performance limited by maximal aerobic power.

Peak $\dot{V}O_2$ was not measured in this field study. However, it has already been suggested that this type of performance,

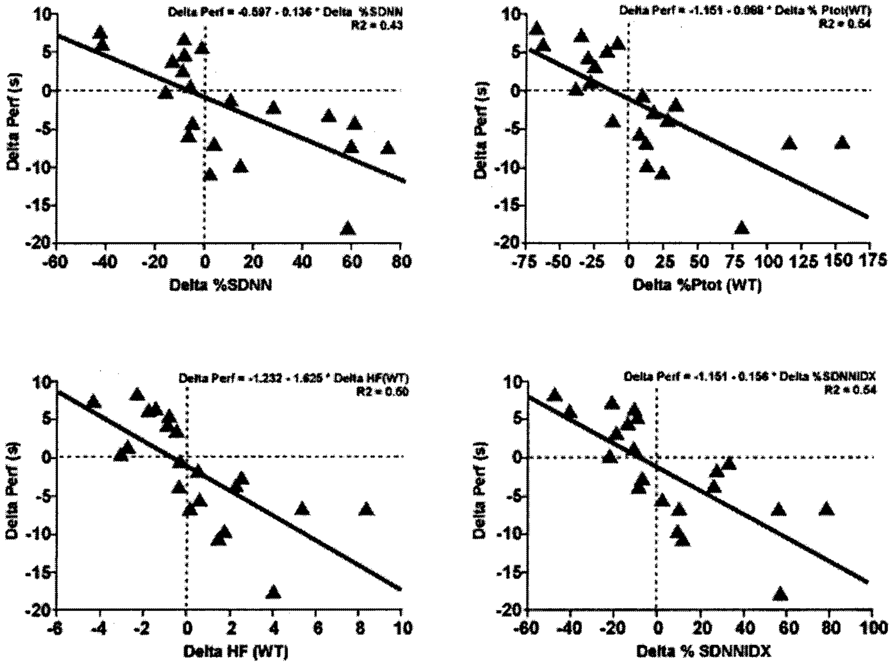
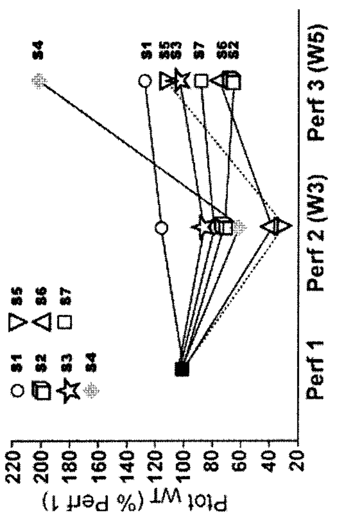


FIGURE 3—Simple regression relationships between variations in HRV indices (SDNN, SDNNIDX, Ptot$_{wavelets}$, HF$_{wavelets}$) and variations in performance.

TABLE 2. Relative values of selected wavelet transform indices of HR variability the night before each performance assessment for the seven swimmers. Relative values are expressed in percentages of baseline HRV.

	Ptot$_{Wavelets}$ (ms^2)			LF$_{Wavelets}$ (ms^2)			HF$_{Wavelets}$ (ms^2)		
	Perf$_1$	Perf$_2$	Perf$_3$	Perf$_1$	Perf$_2$	Perf$_3$	Perf$_1$	Perf$_2$	Perf$_3$
S1	100	118	128	100	96	112	100	179	171
S2	100	73	64	100	82	96	100	66	46
S3	100	83	108	100	48	98	100	71	121
S4	100	61	215	100	67	236	100	49	188
S5	100	32	113	100	24	93	100	37	147
S6	100	37	70	100	34	83	100	15	47
S7	100	75	88	100	69	81	100	79	86
Mean	100	68	112	100	100	114	100	71	115
SD	0	29	50	0	0	54	0	53	57



The figure is a graphical representation of the individual evolution of Ptot$_{Wavelets}$ values recorded on each performance assessment.

400-m freestyle swimming, is a good representation of maximal aerobic power (10). Furthermore, the average performance reached here suggests a maximal aerobic effort (4,5). Previous cross-sectional and longitudinal studies reported a relationship between maximal ANS activity and maximal oxygen consumption (17,24), as well as between ANS activity and performance (24,26). On the other hand, in highly trained athletes, a variation in performance might not necessarily be related to a variation in maximal oxygen consumption. Also, Portier did not report any significant relationship between variations in ANS activity and performance (27).

It was demonstrated that nocturnal urinary norepinephrine excretion is associated with the individual relative performance performed the following day (18). Also, Uusitalo (29) reported an increased sympathetic activity following intensive training, but an association between global HRV and performance. Using HRV indices, we did not find any outstanding sympathetic activity index particularly predicting performance on the following day. However, our data shows that several autonomic nervous system indices have a similar prediction capacity, on the parasympathetic as well as on the sympathetic arm. This underscores our contention that sympathetic and parasympathetic activity cannot be artificially considered separately. They are both associated with performance. Although some differences in their respective activity can be observed under extreme conditions, normally they do not diverge widely, demonstrating their interdependence through their common evolution.

Few studies have focused on individual ANS activity, as many have explored the group responses. In the present study, even though the sample was small, individual ANS activity–performance relationships were strikingly strong, suggesting the potential use of HRV in follow-up and control of training. Interestingly, the relationship was masked at the group level. This factor might be an explanation for the contradictory results reported in the literature as to the relationship between ANS activity and performance and/or training load.

Notably, the recording and the analysis method, as well as the recording time, might have led to contradictory results, so we chose to measure ANS activity during the night. At night, when the autonomic nervous system is in charge of the biological equilibrium of the organism only, not having to take care of the environmental inputs such as light, noise, and emotional or professional stimulations (29). In daytime conditions, it may not be possible to measure autonomic indices in order to establish the relationship between autonomic nervous system activity and maximal performance. In such cases, the autonomic nervous system mainly reflects the answer to external stimuli. Also, recording ANS activity during the night allows for a recording of performance the following day; this was not necessarily the case in previous studies. Regarding the work done by Furlan (12), it appears necessary to record both ANS activity and performance in the closest time span. All of this might explain the contradictory results found in the bibliography regarding the evolution of ANS activity in response to the training load, as well as its association with performance.

Although it is also driven by the autonomic nervous system, nocturnal heart rate was a weaker predictor of performance than HRV. Adding the fact that absolute variations in heart rate are small, heart rate is a weaker marker of training load or fatigue than HRV.

Selected indices from the straightforward time-domain analysis method yielded as strong relationships as the wavelet transform indices did when we compared variations in performances with variations in ANS activity. This has practical implications in routine use, as time-domain indices are easily calculated. However, a better separation of HRV status (spectral analysis) between consecutive weeks was observed when using values normalized to the first recording of each subject considered as the 100% reference value. This suggests that each subject has his own autonomic nervous system equilibrium level, in absolute values. However, the individual modification follows common rules, allowing an individual insight into the effects of training load on the autonomic regulation. A longer follow-up over a complete season would be necessary to better test this hypothesis.

One of the athletes presented a 10-s improvement in performance without a significant change in autonomic activity (S_5, Table 2). This is explained by the fact that his initial performance recorded was far below his season best, unlike the other subjects. Therefore, the baseline HRV–performance association was not as representative as in the other subjects, and the following recordings during the intensive training period and the second recovery period were somewhat distorted. Performance achievement is the result of the complex interaction of many factors. Modeling along several consecutive periods of training and associating ANS activity indices, with further performance factors, such as training load, would be very useful in attempting to predict performance.

Interestingly enough, autonomic nervous system activity may well summarize the multiple parameters of physical training. As quantifying precisely physical training loads is very challenging, the promising complex theoretical models proposed to date (3,6,7,22) are still somewhat inadequate for routine use. Physical workload should take into consideration both training sessions (intensity, volume, and density of training) and other complementary daily activities (daily activity). HRV measured during sleep provides an indicator of the accumulated total strain of both training and other sources of stress to the athlete. Moreover, these measurements can be easily performed with practical tools that impose minimal inconvenience on the athlete. HRV indices thus appear to be promising tools in the control and follow-up of the effects of training load and daily activity on performance or fitness, based on our results in young swimmers. Nocturnal autonomic nervous system activity measurements have been used to monitor the effects of training and to optimize tapering and its relationship with performance, and more particularly with maximal aerobic power performance variations, making ANS activity a promising variable to feed system model theories of performance prediction.

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