Training Organization, Physiological Profile and Heart Rate Variability Changes in an Open-water World Champion

Authors

Robin Pla[1,2,3], Anael Aubry[1], Noémie Resseguier[4], Magali Merino[2], Jean-François Toussaint[3,5], Philippe Hellard[2,3]

Affiliations

1 EA7370, Institut National du Sport de l'Expertise et de la Performance, Paris, France
2 Fédération Française de Natation, Seine Saint-Denis, Pantin, France
3 IRMES EA7329, Institut National du Sport de l'Expertise et de la Performance, Paris, France
4 Public Health Department-Research Unit EA3279, AMU, Aix Marseille Université, Marseille, France
5 Assistance Publique - Hopitaux de Paris, Center for Sports Medicine Research, Paris, France

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Bibliography

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Correspondence

Mr. Robin Pla
Institut National du Sport de l'Expertise et de la
Performance, Paris,
11 avenue du Tremblay,
Paris
75012,
France
Tel.: + 33/640/532 608, Fax: + 33/640/532 608
robinpla38@gmail.com

ABSTRACT

This case study reports the training of an elite 25-km open-water swimmer and the daily heart rate variability (HRV) changes during the 19-week period leading to his world champion title. Training load was collected every day and resting HRV was recorded every morning. The swimmer's characteristics were $\dot{V}O_{2max}$: 58.5 ml · min^{-1} · kg^{-1}, maximal heart rate: 178 beats per minute, and maximal ventilation: 170 L · min^{-1}. Weekly training volume was 85 ± 21 km, 39 ± 8 % was at $[La]_b < 2$ mmol · L^{-1} (Z1), 53 ± 8 % was at $[La]_b$ 2–4 mmol · L^{-1} (Z2), and 8 ± 4 % was at $[La]_b > 4$ mmol · L^{-1} (Z3). In the supine position, the increase in training volume and Z2 training were related to increases in rMSSD and HF. In the standing position, an increase in parasympathetic activity and decrease in sympathetic activity were observed when Z1 training increased. Seasonal changes indicated higher values in the LF/HF ratio during taper, whereas higher values in parasympathetic indices were observed in heavy workload periods. This study reports extreme load of an elite ultra-endurance swimmer. Improvements in parasympathetic indices with increasing Z2 volume indicate that this training zone was useful to improve cardiac autonomic activity, whereas Z1 training reduced sympathetic activity.

Introduction

Case studies reported training organization of ultra-endurance athletes in running, triathlon, cross-country skiing and cycling [1–4]. In these case studies, the athletes put in more than 1 500 h yearly, with an average of 14 ± 2 sessions per week [1, 3, 4]. Very high yearly training volumes have been observed for cyclists: 24 000 km [5], runners: 10 000 km [6], and swimmers: 3 500 km [7], corresponding to 28 ± 3 h per week. An Olympic triathlete reported 796 sessions across a 50-week Olympic season [3]. The periodization of extreme training loads includes specific periods like in training camps, during which these high training loads are concentrated for 2–5 weeks. These training peaks are sometimes associated with an overreaching state [8, 9], characterized by a short-term performance decrement without severe negative symptoms [10].

Like other ultra-endurance sports, open water swimming implies regular training peaks, with three major events: 5 km, 10 km, and 25 km, lasting approximately 1, 2, and 5 h, respectively. Its popularity has grown since the 10-km event entered the Olympic program in 2008 [11]. Few studies have focused on the training characteristics of elite open-water swimmers [12–14]. Reports on elite open-water swimmers indicated a high training volume (74–86 km, > 24 h per week) with 10 sessions per week and an intensity distribution of 74–89 % in zone 1, 10–28 % in zone 2, and 1–8 % in zone 3 [12–14]. These data confirm an extreme training load in terms of volume, intensity, and frequency that is notably characterized by a pyramidal intensity distribution [15]. A body of work has underlined the importance of monitoring athletes' adaptive responses to these very high training loads to prevent fatigue, a non-functional overreaching state, illness, and injuries, and to improve the physiological adaptations [9, 10, 16–18]. The non-functional overreaching state can appear when athletes do not respect the balance between training and recovery, which leads to a short-term decrement in performance [10].

Among the set of indices used to monitor athletes' adaptations to high levels and frequencies of training and competition (questionnaires, biological measures), heart rate variability (HRV) is one of the most informative and is easy to obtain. HRV provides insight into cardiac autonomic balance with parasympathetic and sympathetic activity [19–21]. Some studies have shown decreased parasympathetic activity and increased sympathetic activity in the non-functional overreaching states in elite athletes [22–25]. The increase is due to excessive intense training, a severe training volume, and elevated stress factors [26, 27]. Other results have demonstrated an increase in parasympathetic activity, which has been interpreted as an extreme fatigue state [28, 29]. The non-functional overreaching state is frequently observed in endurance athletes and is characterized by the suppression of sympathetic regulation and lower heart rate values during training at all intensities [29]. Certain HRV responses, like a decline in the high-frequency (HF) power band, are associated with a high risk of all types of fatigue, whereas an increase in the low-frequency (LF) power band is associated with a higher risk of muscular affections [30].

The monitoring of heart rate variability allows for an individual response of training load and physiological stress during specific periods. Hug showed that a reduction in the training load decreased the parasympathetic activity at the end of a taper period for marathon runners [31]. Edmonds observed similar results for elite young rugby players, with a predominant sympathetic modulation before the game [32]. Other authors have argued that the inhibition of vagal mechanisms is reduced in this period, whereas sympathetic activity helps to prepare the cardiovascular system for rapid and large variations in heartbeat, blood flow, and the redistribution of blood flow for demanding competitions [23].

The present study aimed to investigate how daily HRV analysis can help training load monitoring for ultra-endurance swimmers, providing new insights on training organization in this sport [12, 13].

Materials and Methods

Participant

An elite male swimmer (age: 23 years, height: 191 cm, body mass: 82.7 kg, BMI: 22.7, fat mass: 8.1 %, $\dot{V}O_{2max}$: 58.5 $m \cdot min^{-1} \cdot kg^{-1}$) has been a member of the French open-water team since 2012. He was the 25-km European champion in 2014 and 2016 and the 25-km world champion in 2017. During the study period, he underwent various physiological and physical tests, which are shown in ▶ **Table 1**. The swimmer gave written informed consent for publication of the results of this study. This study was conducted in accordance with recognized ethical standards and the national/international laws reported by Harriss and Atkinson [33].

Physiological characteristics

During this 19-week period, physiological tests were performed.

5 × 200 m incremental test

The swimmer performed an incremental test in freestyle to determine maximal aerobic speed (MAS) and the speed corresponding to 4 $mmol \cdot L^{-1}$ (V4mmol $\cdot L^{-1}$). This test consisted of swimming 5 × 200 m with the final 200 m swum at maximal effort and with increments of 0.05 $m \cdot s^{-1}$ and 45 s of rest between each 200 m stage [34]. The initial speed was established according to the swimmer's individual performance in the 400 m freestyle. Swim velocity was imposed using an audible signal. Every 200 m, capillary samples for blood lactate $[La]_b$ were collected at the finger and were analyzed with a Lactate Pro 2 analyzer (Arkray, Inc., Kyoto, Japan). Gas analysis for peak oxygen consumption ($\dot{V}O2_{peak}$) was conducted immediately after the end of the test using a K4b2 gas analyzer (Cosmed, Rome, Italy) connected to a face mask (Hans Rudolph, Inc., Shawnee Mission, KS, USA). As soon as the swimmer's head was out of the water, the mask was put on him for 30 s. The first 20 s were used for the analysis to determine $\dot{V}O_{2peak}$[35]. Heart rate measures were collected with a Garmin Swim Belt (Garmin, Olathe, KS, USA).

10 km time trial

The swimmer swam 10 km in a swimming pool to measure physiological capacities during this event. The test consisted of performing the best total time possible. Capillary samples for blood lactate $[La]_b$ were collected at the finger during the 45 s rest interval after each step of the test: after 500 m, 3 500 m, 7 000 m, 8 500 m and 10 000 m. Gas analysis for $\dot{V}O_{2peak}$ was conducted immediately after the end of the test using the K4b2 gas analyzer (Cosmed, Italy) connected to a face mask (Hans Rudolph, Inc., USA). As soon as the swimmer's head was out of the water, the mask was put on for 30 s. The first 20 s were used for the analysis to determine $\dot{V}O_{2peak}$[35]. Heart rate measures were collected with the Garmin Swim Belt (Garmin, USA). Biomechanical parameters like stroke rate and stroke length were estimated using TritonWear Technology (TritonWear, Toronto, Canada).

▶ **Table 1** Performance and physiological characteristics of 25-km open-water world champion during 10-km and incremental test 5 × 200 m.

	10 km	**5 × 200 m**
Duration (min)	119.3	13
Speed on last 200 m ($m \cdot s^{-1}$)	1.56	1.68
VO_2 peak ($L \cdot min^{-1}$)	4.67	4.59
VO_2 peak ($mL \cdot min^{-1} \cdot kg^{-1}$)	58.5	56.4
VE ($L \cdot min^{-1}$)	170	168
Max heart rate	175	178
Peak blood lactate ($mmol \cdot L^{-1}$)	4.0	8.5
Stroke rate ($c \cdot min^{-1}$)	34.0	41.0
Stroke length (m)	2.63	2.55

Training

Training was quantified over the 19 weeks before the open-water world championships. Per week, the swimmer had 10 ± 1 in-water training sessions and one strength training session. A half-day per week was dedicated to full rest (Wednesday afternoon). All training sessions were monitored by the same coach, who shared her training diary with the physiologist. Intensity distribution was quantified as proposed by Mujika [34]. Volumes in training zones were categorized as the volume accumulated below the speed corresponding to $[La]_b < 2\,mmol \cdot L^{-1}$ (Z1), $[La]_b$ between $2\,mmol \cdot L^{-1}$ and $4\,mmol \cdot L^{-1}$ (Z2), and $[La]_b > 4\,mmol \cdot L^{-1}$ (Z3). This quantification was made on the basis of a 10 × 400 m incremental test with blood lactate collection (▶ **Table 2**). This test was performed to determine the relationship between blood lactate concentration and swimming speed. The speeds corresponding to each intensity level were then corrected to account for the swimming distance and rest intervals using Olbrecht's method [36]. Typical training set in zone 1, 2, and 3 were respectively 50 × 100 m with 15 s rest swum in 1:08 min:s with $[La]_b = 1.2\,mmol \cdot L^{-1}$, 15 × 100 m with 40 s rest swum in 1:04 min:s with $[La]_b = 3.5\,mmol \cdot L^{-1}$, and 8 × 50 m with 30-s rest swum in a mean 28.2 s with $[La]_b = 6.4\,mmol \cdot L^{-1}$. In order to normalize the intensity values, the training volume at each intensity level was expressed as a percentage of the maximum volume at the same intensity achieved over the course of the study [37]. The global weekly training load was the mean of the percentages of these three intensity zones.

▶ **Table 2** Time and $[La]_b$ in an incremental test 10 ×400 m each 5'.

Lap	Time (min:sec)	$[La]_b$ ($mmol \cdot L^{-1}$)
1	4:33.22	0.9
2	4:28.09	0.9
3	4:26.18	0.9
4	4:23.80	1.3
5	4:21.15	0.9
6	4:19.37	0.8
7	4:15.83	1.0
8	4:12.10	2.0
9	4:11.80	2.3
10	4:07.96	4.3

The training period comprised eight mesocycles (▶ **Table 3**) as follows. The week before the Abu Dhabi World Cup was characterized by low training volume and relatively high intensity work (General). An initial 2-week taper period to prepare for a major pool competition was characterized by low training volume and relatively high-intensity work (Taper 1). Three weeks in training camp were characterized by high volume and a high quantity of work around the speed corresponding to $4\,mmol \cdot L^{-1}$ (Training camp 1). Four weeks of specific training were characterized by a medium training load and long series performed at race pace (Specific). A new 3-week taper period that ended with the French Open Water Championships was characterized by a sharp reduction in training volume (Taper 2). A week-long transition period was characterized by low training volume and no high-intensity exercise (Transition) before leaving for a second 3-week training camp, which was characterized by high volume and extensive work around the speed corresponding to $4\,mmol \cdot L^{-1}$ (Training camp 2). Last, a final 2-week preparation period that ended with the World Open Water Championships was characterized by a reduction in training volume and a rise in high intensity work (Taper 3).

Heart rate recordings

The HRV protocol test was performed as proposed and described by Schmitt [21]. Each test was conducted in the morning just after awakening [38]. For most of the tests, the wake-up time was the same because the swimmer followed the same training schedule over the 19 weeks. The same routine was used for every test recording, with the test lasting 8 min in the supine position, then 7 min in the standing position [39]. RR intervals were recorded with a heart rate belt (Polar H7, Polar Electro Oy, Kempele, Finland) and transmitted by Bluetooth using a smartphone application (Elite HRV, USA). RR interval recordings were analyzed from the last 256 s of each position. Breathing rate was not guided. All RR recordings were visually inspected for stationarity and corrected for artifacts and ectopic beats via Kubios's in-built piecewise cubic spline interpolation [32]. Data were always inspected by the same researcher. Kubios software (v2.0, University of Kuopio, Finland) allowed calculating time and frequency domain variables. Spectral power was calculated by the fast Fourier transform (FFT).

▶ **Table 3** Overview of the training performed during each training mesocycle.

Mesocycle	Date	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
General	AM	Low intensity	Mixed	Aerobic + HIT	Low intensity	Mixed	Long distance	Rest
	PM	Lactate threshold	Test	Rest	Lactate threshold	Test	Rest	Low intensity
Specific	AM	Low intensity	Mixed	Long distance	Low intensity	Mixed	Long distance	Rest
	PM	Lactate threshold	Test	Rest	Lactate threshold	Test	Rest	Easy
Training camp	AM	Low intensity	Mixed	Long distance	Low intensity	Mixed	Long distance	Mixed
	PM	Lactate threshold	Test	Easy	Lactate threshold	Test	Low intensity	Easy
Taper	AM	Low intensity	Mixed	HIT	Low intensity	Mixed	Long distance	Rest
	PM	Lactate threshold	Test	Rest	Lactate threshold	Test	Rest	Very easy

Note: low intensity = $[La]_b < 2\,mmol \cdot L^{-1}$, lactate threshold = $2\,mmol \cdot L^{-1} < [La]_b < 4\,mmol \cdot L^{-1}$, mixed = both low intensity and lactate threshold, test = physiological tests, HIT = high intensity training and $[La]_b > 4\,mmol \cdot L^{-1}$, long-distance = set with long distance intervals and $[La]_b$ near to $4\,mmol \cdot L^{-1}$, easy = very low intensity, rest = no training.

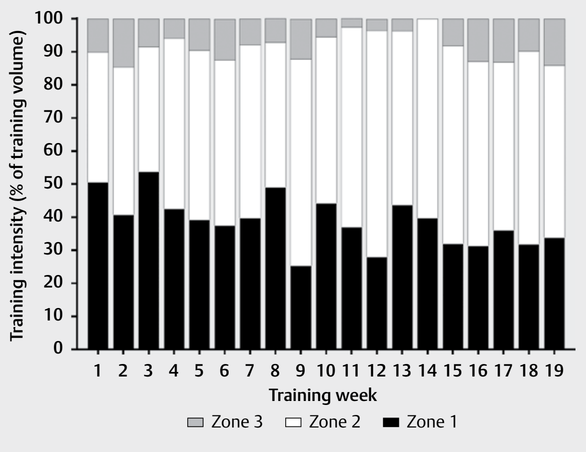
Statistical analysis

A descriptive analysis of heart rate variability parameters was performed, using medians and interquartile ranges (IQRs). These parameters were then described and compared according to training condition-related variables (total training volume, volume in each intensity zone, mesocycle). The Kruskal-Wallis test was used for non-binary qualitative variables, given the limited number of observations. Each daily HRV parameter was compared with the previous daily training variable. To assess when substantially higher amounts of volume per day were spent at a particular intensity, for every intensity zone four groups were organized according to the percentage of the mean daily volume spent in the zone (between 0 and 50 %, between 50 and 100 %, between 100 and 150 %, and more than 150 %). The effect of the day on the HRV responses was described using time series methods, with seasonal decomposition by a moving average strategy, the day being considered as a seasonal parameter. The change in heart rate parameters over time was analyzed using Box-Jenkins method-based seasonal autoregressive integrated moving average (SARIMA) models, which allow trend changes and seasonal changes to be accounted for. Pre-estimation of these models was based on stationarity, autocorrelation, and partial autocorrelation functions. Goodness of fit was assessed using residual autocorrelation (Bartlett's test with noise test, Portmanteau Q test) and residual normality. All tests were two-sided, and $p < .05$ was considered significant. All data were analyzed using R software.

Results

Physiological characteristics

▶ **Table 1** presents the swimmer's main physiological characteristics observed during the study period. Data show maximal ventilation of $170 \cdot \text{min}^{-1}$ and physiological characteristics at the end of the 10 km, which reached higher values than in the incremental test. ▶ **Table 2** shows the speed–blood lactate concentration relationships during the 10 × 400 m incremental test. This table shows $[\text{La}]_b = 2\,\text{mmol} \cdot \text{L}^{-1}$ corresponding to 63.2 s per 100 m ($1.58\,\text{m} \cdot \text{s}^{-1}$) and $[\text{La}]_b = 4\,\text{mmol} \cdot \text{L}^{-1}$ corresponding to 62.0 s per 100 m ($1.61\,\text{m} \cdot \text{s}^{-1}$).



▶ **Fig. 1** Weekly training intensity distribution expressed as a percentage of total training volume over the 19 weeks before the 25-km world championships.

Training

During the study period, the mean total training per week was 28 ± 4 h, corresponding to 85 ± 21 km per week. The training intensity distribution is shown in ▶ **Fig. 1**. The mean percentage of total training volume was 39 ± 8 % in zone 1, 53 ± 8 % in zone 2, and 8 ± 4 % in zone 3. The first part of the training period showed a higher percentage swum in zone 1 (between 40 and 50 %) than the second part (between 30 and 40 %). The total training load is shown in ▶ **Fig. 2**. The training period was characterized by two peaks in the load at the two training camps, with a 40 % improvement, and maximal volume reached 120 km per week over the 14 sessions. The taper period showed a progressive decrease in training load in the 3 weeks before the world championships.

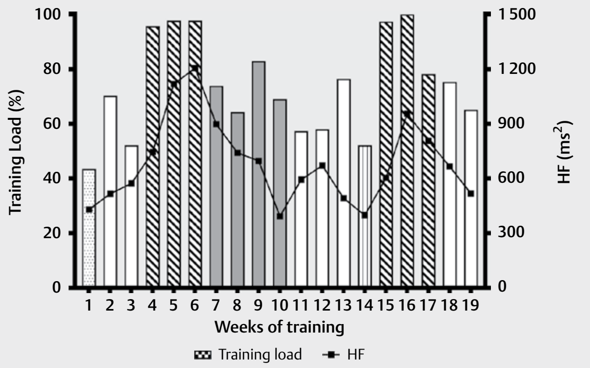
Heart rate-based variables

Intensity distribution

The relationships between HRV parameters and training intensity zones are presented in ▶ **Table 4a**, **b**.

In the supine position, a continuous increase in total training volume and zone 2 training revealed higher values in parasympathetic indices ($p < 0.05$ for rMSSD and HF). The LF/HF activity was also related to the increase in volume spent in zone 2 ($p < 0.05$). No significant results were observed for zones 1 and 3 ($p > 0.05$).

In the standing position, the increased volume in zone 1 was related to higher values for HF ($p < 0.05$). At the same time, the LF/HF ratio continuously decreased ($p < 0.05$). No significant changes were observed for other training variables.



▶ **Fig. 2** Weekly total training load expressed in a percentage of the maximal weekly training load over the 19 weeks before the 25-km world championships. The hatched column represents training camps characterized by endurance training. The white column represents taper phases ending in major competition at the end of the period. The gray column represents specific training between the training camp and the taper. The crossed column represents the transition phase between the French championships and the training camp. The dotted column represents the first training period with a high state of fatigue before the Abu Dhabi World Cup.

▶**Table 4a** Median (interquartile range) for HRV parameters in supine position depending on group training variables (expressed as the percentage of the mean daily volume spent in the zone observed). Each daily HRV parameter was compared with the previous daily training variable.

		HR (bpm)	**RMSSD (ms)**	**LF (ms^2)**	**HF (ms^2)**	**LF/HF**	**LF + HF (ms^2)**
Total volume	*0 to 50%*	51 (49–53)	44 (39–52)	1538 (938–1852)	561 (313–710)	2.7 (2.2–3.0)	2099 (1532–2583)
	50 to 100%	52 (49–55)	47 (38–57)	1501 (885–2761)	531 (406–822)	3.1 (2.0–4.8)	2240 (1341–3578)
	100 to 150%	51 (50–53)	50 (47–53)	2224 (1809–2614)	673 (599–742)	3.4 (1.9–3.8)	2958 (2368–3341)
	> 150%	51 (49–55)	56 (42–66)	1856 (1378–2677)	866 (524–1101)	2.6 (1.8–3.5)	2729 (1877–3851)
	p-value	0.590	0.019	0.041	0.014	0.285	0.030
Z1	*0 to 50%*	52 (50–53)	45 (41–55)	1618 (1198–2282)	594 (369–818)	2.8 (2.3–3.8)	2145 (1871–3084)
	50 to 100%	52 (49–55)	47 (36–53)	1353 (842–2716)	520 (359–748)	2.5 (1.6–4.8)	2135 (1257–3160)
	100 to 150%	51 (49–54)	54 (43–60)	2050 (1628–2722)	676 (513–972)	2.9 (2.0–3.6)	2779 (2082–3812)
	> 150%	51 (49–55)	53 (41–61)	1790 (1061–2551)	679 (544–1024)	3.0 (1.7–3.8)	2393 (1514–3658)
	p-value	0.960	0.081	0.122	0.114	0.890	0.139
Z2	*0 to 50%*	52 (50–53)	43 (40–51)	1607 (1010–2244)	531 (312–637)	2.7 (2.3–5.4)	2071 (1523–2966)
	50 to 100%	52 (50–55)	45 (36–53)	1673 (910–2349)	588 (363–674)	3.1 (2.5–4.2)	2315 (1292–3149)
	100 to 150%	51 (49–54)	52 (43–60)	1731 (1189–2625)	723 (500–934)	2.3 (1.7–3.5)	2431 (1803–3714)
	> 150%	50 (48–54)	58 (50–66)	2273 (1592–2926)	897 (564–1101)	2.8 (2.0–3.7)	3184 (2333–3968)
	p-value	0.192	0.001	0.138	0.002	0.186	0.037
Z3	*0 to 50%*	51 (49–54)	48 (41–56)	1673 (1003–2565)	600 (449–849)	2.7 (1.8–3.8)	2389 (1598–3497)
	50 to 100%	49 (48–53)	55 (51–65)	1896 (1290–2497)	853 (634–988)	2.8 (2.1–3.6)	2749 (1968–3675)
	100 to 150%	51 (50–55)	48 (37–57)	1731 (1269–2241)	633 (421–892)	2.8 (1.9–3.5)	2639 (1665–3040)
	> 150%	53 (50–54)	50 (40–60)	1960 (1205–2739)	613 (386–893)	3.0 (2.1–4.3)	2584 (1788–3647)
	p-value	0.419	0.480	0.883	0.588	0.783	0.857

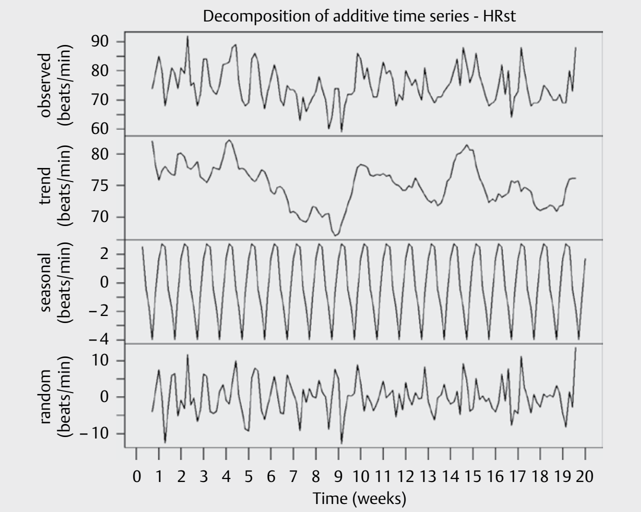
▶**Table 4b** Median (interquartile range) for HRV parameters in standing position depending on group training variables (expressed as the percentage of the mean daily volume spent in the zone observed). Each daily HRV parameter was compared with the previous daily training variable.

		HR (bpm)	**RMSSD (ms)**	**LF (ms^2)**	**HF (ms^2)**	**LF/HF**	**LF + HF (ms^2)**
Total volume	*0 to 50%*	75 (72–81)	11 (9–12)	477 (284–730)	13 (9–19)	36 (26–53)	490 (294–741)
	50 to 100%	75 (71–79)	13 (10–14)	523 (333–752)	15 (9–28)	35 (21–53)	533 (339–782)
	100 to 150%	73 (70–74)	11 (10–14)	540 (344–816)	20 (7–31)	29 (19–50)	552 (254–886)
	> 150%	76 (70–82)	12 (9–14)	441 (288–664)	20 (11–30)	26 (14–39)	485 (354–692)
	p-value	0.388	0.556	0.675	0.348	0.117	0.777
Z1	*0 to 50%*	75 (71–80)	11 (10–13)	433 (276–552)	12 (8–19)	28 (23–52)	449 (288–564)
	50 to 100%	75 (71–80)	12 (10–14)	530 (332–861)	15 (9–28)	37 (25–54)	541 (338–880)
	100 to 150%	74 (70–78)	12 (9–14)	509 (323–664)	15 (8–30)	36 (19–47)	526 (360–696)
	> 150%	75 (69–83)	13 (10–14)	504 (383–665)	24 (19–35)	21 (9–30)	549 (402–724)
	p-value	0.799	0.578	0.591	0.033	0.042	0.496
Z2	*0 to 50%*	73 (70–79)	11 (10–13)	502 (283–884)	15 (9–20)	29 (22–47)	518 (293–900)
	50 to 100%	75 (70–81)	12 (10–15)	501 (366–679)	13 (9–35)	35 (19–51)	525 (373–823)
	100 to 150%	73 (71–78)	12 (10–14)	523 (322–754)	19 (11–29)	28 (19–45)	548 (351–784)
	> 150%	79 (75–81)	9 (9–13)	423 (316–629)	13 (8–23)	37 (24–51)	438 (324–650)
	p-value	0.073	0.136	0.511	0.462	0.723	0.442
Z3	*0 to 50%*	75 (71–80)	12 (9–13)	505 (331–743)	16 (8–28)	34 (23–53)	521 (338–766)
	50 to 100%	73 (71–76)	12 (10–14)	599 (308–745)	21 (11–27)	29 (18–48)	634 (317–771)
	100 to 150%	74 (73–81)	11 (9–17)	509 (337–967)	11 (8–50)	36 (21–46)	523 (344–1195)
	> 150%	73 (68–82)	12 (10–15)	431 (275–577)	20 (11–33)	25 (13–42)	485 (316–594)
	p-value	0.476	0.756	0.796	0.388	0.098	0.902

Seasonal changes (day of the week and mesocycles)

In the standing position, heart rate changed over the week, with an increase from Saturday (median: 71, IQR: 68–74) to Wednesday (median: 79, IQR: 74–83), and then a decrease until the following Saturday (▶**Fig. 3**).

Orthosympathetic predominance was observed for the mesocycles during taper phases, whereas parasympathetic activity showed higher values during heavy training periods (▶**Table 5a,** and **b**).



▶ **Fig. 3** Time series for heart rate in standing position across the 19-week study period, and its decomposition according to the additive model, i. e., Y[t] = T[t] + S[t] + e[t], where Y[t] is the observed time series, T[t] is the trend component (over the 19-week period in the present time series), S[t] is the seasonal component (week in the present time series), and e[t] is the error component.

Time domain vs. spectral analysis

▶ **Fig. 4** shows daily differences between $rMSSD_{rollave}$ and $HF_{rollave}$ in supine position. During the study period, $rMSSD_{daily}$ and HF_{daily} were highly correlated: r = 0.91 (0.87,0.93; $p < 0.001$). rMSSD had a smaller CV (CV = 27.85) than HF (CV = 55.66).

Discussion

In the present study, we analyzed the morning resting HRV responses in a world champion open-water swimmer who completed a heavy training load, and we show his extreme physiological capacities. The major results of this study were: (1) a speed of 1.61 $m \cdot s^{-1}$ associated with $[La]_b = 4\,mmol \cdot L^{-1}$; (2) a weekly training volume of 85 km, which highlights the high weekly training volume in elite open-water swimmers, as previously reported in the literature [12]; and (3) an increase in parasympathetic activity during severe training loads and a possible orthosympathetic predominance in taper periods due to a decrease in parasympathetic activity.

Training load

A mean weekly training volume of 85 km, ranging as high as 120 km and corresponding to 28 h per week, confirms previous data reported in the literature for elite open-water swimmers [12]. Two studies described similar weekly training volumes between 74 and 86 km for international open-water swimmers [12, 14].

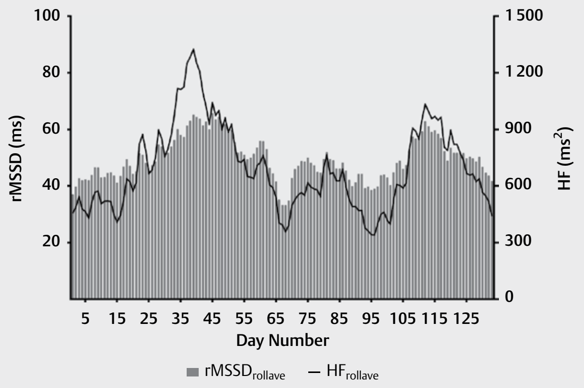
The training intensity distribution showed a model with a large part of the training conducted between $[La]_b = 2\,mmol \cdot L^{-1}$ and $[La]_b = 4\,mmol \cdot L^{-1}$. Reports on elite rowers, triathletes, skiers, and marathoners have indicated lower training proportions around the lactate threshold (1–5 %) [3, 4, 40]. A recent study confirmed that Olympic open-water swimmers adopted a model with a large part

▶ **Table 5a** Median (interquartile range) for HRV parameters in supine position across the different cycles of the study period before the open-water world championships.

	p-value	General	Taper 1	Training camp 1	Specific	Taper 2	Transition	Training camp 2	Taper 3
HR (bpm)	0.006	54 (53–57)	53 (51–55)	50 (49–54)	49 (47–51)	51 (50–52)	52 (51–54)	54 (50–55)	53 (50–53)
rMSSD (ms)	0.004	41 (34–45)	47 (39–53)	60 (47–68)	52 (44–58)	47 (38–59)	39 (36–52)	56 (44–63)	49 (40–54)
LF (ms^2)	0.410	2034 (1203–2317)	1795 (1032–2734)	2200 (1116–2665)	1530 (957–1790)	1963 (1241–3473)	865 (814–1111)	1868 (1419–2929)	1927 (1488–2165)
HF (ms^2)	0.002	401 (252–657)	544 (382–644)	1071 (599–1386)	625 (518–908)	535 (450–699)	287 (254–372)	832 (501–991)	594 (344–816)
LF/HF	0.001	4.1 (3.1–5.4)	3.1 (2.3–5.5)	2.0 (1.6–2.4)	2.7 (1.5–3.1)	3.3 (2.5–5.1)	3.2 (3.0–3.3)	2.8 (2.0–3.4)	3.4 (2.4–4.8)
LF + HF (ms^2)	0.227	2380 (1556–2992)	2574 (1396–3470)	3521 (1831–4035)	2386 (1598–2826)	2692 (1719–3999)	1141 (1113–1427)	2810 (1877–4056)	2367 (1994–2916)

▶ **Table 5b** Median (interquartile range) for HRV parameters in standing position across the different cycles of the study period before the open-water world championships.

	p-value	General	Taper 1	Training camp 1	Specific	Taper 2	Transition	Training camp 2	Taper 3
HR (bpm)	0.042	79 (74–83)	75 (74–82)	76 (70–83)	72 (70–74)	74(72–79)	80 (76–85)	75 (71–80)	73(70–75)
rMSSD (ms)	0.038	9 (7–10)	12 (11–14)	13 (10–14)	13 (11–16)	12 (9–14)	12 (12–12)	10 (9–13)	11 (11–14)
LF (ms^2)	0.163	339 (246–516)	539 (416–946)	417 (269–546)	540 (331–1003)	496 (325–1037)	477 (428–649)	431 (264–710)	537 (317–672)
HF (ms^2)	0.153	9 (7–12)	16 (11–29)	22 (13–35)	17 (8–40)	16 (9–31)	16 (11–21)	19 (10–26)	15 (8–22)
LF/HF	0.094	32 (25–42)	42 (28–47)	20 (9–32)	28 (19–59)	36 (29–51)	35 (30–54)	27 (20–40)	38 (25–55)
LF + HF (ms^2)	0.209	348 (254–532)	544 (435–964)	517 (322–594)	600 (337–1020)	504 (333–1061)	486 (443–659)	447 (278–744)	545 (324–692)



► **Fig. 4** Daily changes in 7-day rolling average rMSSD and 7-day rolling average HF in supine position.

of the training spent in zone 2, although this volume was lower than that observed in our study [12, 14]. The first hypothesis that might explain this different distribution in swimming compared with other endurance sports is that the cardiac load is lower because of the supine position and the lower muscle mass that is involved [41, 42]. In this case study, low heart rate values were observed for this swimmer after maximal efforts (175–178 bpm) and around the lactate threshold (162–165 bpm, unpublished data). Thus, in swimming, threshold training can induce less cardiac fatigue compared to other endurance sports. The second hypothesis is that the maximal stroke length is attained around the maximal lactate steady state (MLSS) during incremental testing in competitive swimmers [43] and, at this intensity, long-distance swimmers demonstrate a capacity to reduce energy cost with good arm-coordination in order to maximize efficiency [44].

HRV responses to training

The volume increase for swimming speeds between $[La]_b = 2\,mmol \cdot L^{-1}$ and $[La]_b = 4\,mmol \cdot L^{-1}$ was associated with an increase in parasympathetic activity. This result contrasts with previous studies showing an increase in parasympathetic regulation following low intensity training: $< 2\,mmol \cdot L^{-1}$[23, 45–48]. The use of smaller muscle mass [49] and the altered hemodynamics associated with a horizontal body [42] could result in lower parasympathetic activity for swimming at low intensity.

In the standing position, our results showed a reduction in LF/HF ratio and a rise in parasympathetic activity after an increase in the zone 1 training volume. The decline in orthosympathetic dominance might be explained by the decrease in catecholamine activity following an endurance training program [22]. Last, several authors have shown an increase in parasympathetic activity after endurance training in well-trained athletes, associated with an increase in vagal tone [23, 50] and baroreflex sensitivity [23] and a decrease in diastolic blood pressure [51]. For this swimmer, it seems interesting to keep a high volume of training at low and medium intensity to maintain sufficient parasympathetic activity.

The time series decomposition of the HRV records over the 138 days preceding the world championship title revealed the day-to-day changes. The results highlight an increase in heart rate from Sunday to Wednesday and then a decrease until Saturday. It may be that a half-day of rest facilitated the reduction in sympathetic hyperactivity toward the end of the week. The daily HRV analysis gives information on optimal heart rate values and could help the coach to decide whether it is necessary to give the swimmer a day off. Several studies have already noted the importance of controlling the timing of exercise prior to HRV analysis [32, 52, 53], because high-intensity efforts can lead to orthosympathetic hyperactivity for up to 4 days after the exercise session.

Parasympathetic activity was higher at the training camps, where training volume was very high. This has been observed in many studies, with HF in supine position increasing after endurance training [54–57]. Stanley [48] presented very similar results in a case study of an elite triathlete with increasing parasympathetic activity in the load block and increasing sympathetic activity in the taper + race. In contrast, for 8 elite rowers, after an increase in training load from 50–100 % during high-intensity training, Iellamo observed a significant decrease in HF and a significant increase in LF, assuming that high-intensity volume during training peaks could determine the predominance type of cardiac autonomic system [23].

Our results also showed sympathetic predominance during taper phases. As described in elite athletes by other authors [31, 32, 48, 58], the reduction of training volume associated with maintaining or increasing severe intensity can lead to greater sympathetic stimulation. In this period with a lower training load, plasma volume may be reduced and the aerobic stimulation decreases [59], which in turn can reduce parasympathetic activity. The sympathetic predominance may reflect the adaptation of the cardiovascular system when it is maximally mobilized during maximal effort [23]. In other ultra-endurance sports such as the ultra-mountain race, studies have already observed a decrease in vagal modulation [60, 61]. In a recent study, Nuutila et al. pointed out that individually HRV-guided block training seems to provide greater endurance and neuromuscular adaptations than predetermined block training [62]. In this way, daily heart rate variability monitoring can be useful to increase the athlete's ability to adapt to an intense training load [20]. In this case study, daily HRV indices were collected for each training period. This daily HRV analysis could identify an optimal range of values based on the training cycle. It could help the coach to regulate the volume and intensity of training if the HRV values are not within their optimal range.

This study has some shortcomings. First, the intensity training was based on volume in zone and may have overestimated the volume spent in zone 2. Self-reported RPE may be an additional option to quantify training and allows comparing training intensity distribution with other sports and using the TRIMP method to quantify training load, which was lacking in our study. The use of rating of perceived exertion (RPE) also can help to modulate training load, by identifying states of fatigue. In order to better understand HRV responses to training load, the link between HRV and RPE needs to be investigated further in future case studies in elite athletes. The daily HRV analysis was not assessed alongside performance measures, which might have provided better insight into the HRV changes and how they are related to performance. Also, the HRV indices could have been compared with self-reported indices of fatigue.

Practical Applications

These results confirm previous studies, indicating that elite open-water swimmers train between 3 200 and 4 000 kilometers per year. This high training load can be assessed by physiological tests and monitored by HRV analysis, because HRV is sensitive to load variations [60] and its guidance during block training may provide greater physiological adaptations than predetermined block training [62]. The daily HRV analysis could identify optimal values of HRV indices and provide guidance to the coach:

- To increase training volume at low or moderate intensity after a fall in parasympathetic indices during a training camp, or to take a day off to reduce orthosympathetic predominance during the training week;
- To reduce the training volume if the heart rate and LF/HF ratio values are too low in order to increase orthosympathetic predominance during taper.

Both positions (supine and standing) indicated that HRV changes depend on the intensity distribution, underlining the importance of controlling autonomic balance. Furthermore, complementary subjective indices are required to correctly prevent non-functional overreaching.

Conclusion

This study reports unique data on a 25-km open-water world champion, including novel information about the physiological capacities, training volume and intensity distribution of this ultra-endurance athlete. Training camps, recovery phases, and taper periods can lead to changes in training organization and it seems essential to follow the individual adaptations of elite athletes. Daily recording of HRV indices allows observing the day-to-day variations and seems to be an interesting tool to monitor training load and reduce the risk of fatigue. The daily HRV analysis provides a global fitness level, taking into account many environmental factors.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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