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Electroencephalography Response during an Incremental Test According to the $\dot{V}O_2$max Plateau Incidence

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Abstract: $\dot{V}O_2$max is recognized as a key measure in exercise physiology and sports medicine. However, only 20–50% of maximal incremental exercise tests (IET) result in a plateau of $\dot{V}O_2$ ($\dot{V}O_2$pl). To our knowledge, no study has yet examined the possible difference in brain activity during an IET, in $\dot{V}O_2$pl and non-plateau athletes with the same $\dot{V}O_2$max and age. This study aimed to shed light on the central governor hypothesis, namely that the inability to reach a $\dot{V}O_2$pl may be dictated by the brain rather than by a peripheral physical limit. This hypothesis can now be explored using electroencephalography (EEG) during IET, measuring concomitant power in specific frequency bands. Forty-two athletes were divided into two groups: those who practiced endurance sports and those who did not, and were asked to perform an IET. EEG signals and gas exchange were recorded. A $\dot{V}O_2$pl was observed in twenty-two subjects (52%). EEG power increased in all subjects during IET, except in the alpha band, which showed variability, but not significantly (64% increase, 34% decrease, $p = 0.07$). No differences were found between endurance athletes and non-endurance athletes, except for $\dot{V}O_2$max (60.10 ± 6.16 vs. 51.77 ± 6.41, $p < 0.001$). However, the baseline-corrected ratio of EEG power to $\dot{V}O_2$ was found to decrease in all subjects during IET, in the alpha, beta and theta bands. In conclusion, the presence or absence of a $\dot{V}O_2$pl is not related to the type of EEG response during an IET. Nevertheless, the decline in brain and $\dot{V}O_2$ powers/ratios in all frequency bands suggests that aerobic power may be constrained by brain mobilization.

Keywords: EEG; exhausting exercise; maximal oxygen consumption; fatigue; central governor; endurance; cycling

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1. Introduction

The fundamental tenet of maximal oxygen consumption ($\dot{V}O_2max$), positing a threshold in speed or work rate beyond which no further increases in $\dot{V}O_2$ is observed, traces its origins back in the seminal work of Hill and Lupton in 1923 [1]. They observed a limit to the body's ability to use oxygen during exercise, beyond which oxygen consumption reaches a plateau despite increasing exercise intensity. Currently, $\dot{V}O_2max$ is recognized as a key measure in exercise physiology and sports medicine [2,3]. However, it should be noted that the certainty of reaching $\dot{V}O_2max$ requires the observation of a $\dot{V}O_2$ plateau ($\dot{V}O_2pl$), defined as the point at which $\dot{V}O_2$ remains relatively constant despite increasing work rate. Therefore, by definition, diagnosis of $\dot{V}O_2max$ requires a $\dot{V}O_2pl$, whether it occurs at the end of a continuous incremental test, between the final stages of a discontinuous test, or between an incremental test and a subsequent verification test, as Poole and Jones pointed out [4].

The observation that only a subset of participants in an incremental test have a $\dot{V}O_2pl$ highlights the variability inherent in such assessments. Reported incidences vary considerably, ranging from 17 to 94%, even in studies involving more than 50 participants, particularly depending on the definition of $\dot{V}O_2pl$ used [5]. This variability has led to an extensive debate on the conceptualization and diagnosis of $\dot{V}O_2max$ over the last three decades [2,4]. Only 20–50% of $\dot{V}O_2max$ tests result in a plateau according to this definition [6–14]. The low frequency of the $\dot{V}O_2pl$ has been reported by [15].

However, behind the discussion about the absolute necessity of observing a $\dot{V}O_2pl$ to assess true "$\dot{V}O_2max$", and not just a "$\dot{V}O_2peak$" [16–19], lies the fundamental question of the limiting factors of $\dot{V}O_2$. Reasons for the presence of $\dot{V}O_2pl$ in some, but not all, athletes are not yet clear [18]. Lower anaerobic power or capacity has been suggested as a cause of the absence of plateau [19–21]. Furthermore, it has been shown that faster oxygen kinetics, which minimizes the anaerobic contribution to metabolism in the severe intensity range between the respiratory compensation threshold (RCP) and $\dot{V}O_2max$ (or $\dot{V}O_2peak$) during an incremental exercise test (IET), increases the chances of a plateau occurring at $\dot{V}O_2max$ [5].

However, the role of the brain in regulating exercise intensity to exhaustion has been hotly debated [22–25]. More specifically, the brain has been given greater consideration in models describing the factors responsible for continuing or stopping ongoing exercise. Noakes has suggested that unpleasant sensations of fatigue provide useful feedback to the central nervous system and are used as key regulators to stop exhausting exercise before there is a risk of physiological damage [26]. This hypothesis underlines the importance of recording brain activity alongside exercise characteristics and environmental conditions, particularly under conditions of exhaustion. A better understanding of brain responses to exhaustive exercise up to $\dot{V}O_2max$ would rely on a multimodal approach that could combine neurological, physiological, and biomechanical data.

Regarding neurophysiological aspects, two methods are less restrictive and allow body and head movements: near-infrared spectroscopy (NIRS) and electroencephalogram (EEG). Indeed, brain activity has already been studied during high-intensity exercise, notably when performing an IET on an ergobicycle until exhaustion using NIRS [27–30] or EEG [31–33]. EEG provides robust information on changes in cortical potentials, particularly rhythmic activity and frequency of synaptic processes [33–35]. EEG is one of the most pragmatic means of monitoring changes in brain activity in humans during exercise, certainly because it is less intrusive [31,34,36]. EEG is used to measure cortical brain activity, which is categorized into distinct frequency ranges such as alpha (α: 8–12 Hz) and beta (β: 12–30 Hz), each related to different cognitive functions regulated by the brain. Alpha activity, characterized by quite low-frequency oscillations, is associated with perceptual awareness and inhibition of non-essential processing, which facilitates task performance [37,38]. Conversely, beta activity, characterized by high-frequency oscillations, is associated with voluntary contractions, alertness, and arousal, enhancing the perception of stimuli [39–41]. Spectral analysis is a common means of quantifying the frequency content

of these bands, the main result being the power spectral density (PSD), which indicates the strength or energy of variations between frequencies. An increase in oscillations in cortical regions yields to an increase in the EEG's spectral power.

Several studies have coupled EEG recording with a breath-by-breath expired gas system [31,33,34]. EEG activity has generally been recorded during pedaling tests at a constant load without exhaustion [42–45]. It has also been recorded during exercise to exhaustion in an incremental test [31–33,46]. While the role of the prefrontal cortex in exercise tolerance and termination has been investigated [47–50] showing, for example, that the alpha/beta ratio decreased after the subject experienced exercise as "hard" in reference to the Rate of Perception of Exhaustion [51] and then above the RCP [33,47,48], no study has yet examined the relationship between the occurrence of $\dot{V}O_2$pl with EEG response in well-trained athletes.

To our knowledge, no study has yet examined the possible difference in brain activity during maximal incremental testing in $\dot{V}O_2$pl and non-plateau athletes with the same $\dot{V}O_2$max and age. This study aimed to shed light on the central governor hypothesis, namely that the inability to reach a $\dot{V}O_2$pl may be dictated by the brain rather than by a peripheral physical limit. This hypothesis can now be explored using EEG during IET, measuring concomitant power in specific frequency bands. Forty-two athletes were divided into two groups: those who practiced endurance sports and those who did not, and were asked to perform an IET.

We hypothesize that the difference between athletes who reached the plateau of their $\dot{V}O_2$max and those who did not could be present in different EEG characteristics and in EEG/$\dot{V}O_2$ ratios. Specifically, we believe that athletes who do not achieve a $\dot{V}O_2$pl will show a more pronounced decrease in the ratio between EEG power and $\dot{V}O_2$ as metabolic demand increases. To test this hypothesis, we compared, in the $\dot{V}O_2$pl and non-plateau groups of athletes, the relationship between increasing metabolic demand and EEG response by examining the ratios between the α, β, θ (theta) bands of the EEG and $\dot{V}O_2$. The aim was to tackle the possible issue of a decrease in the ratio between metabolic demand and brain activity during physical exercise.

2. Materials and Methods

2.1. Participants Recruitment and Ethical Approval

Forty-two volunteers participated in the experimentation (Table 1).

Table 1. Subjects' characteristics for the incremental exercise test (n = 42).

Subjects	Mean	Standard Deviation (SD)
Age (years)	25.81	4.92
Height (cm)	180.55	6.78
Weight (kg)	73.90	10.71
Body mass index (kg/m^2)	22.59	2.27
$\dot{V}O_2$max (mL·min^{-1}·kg^{-1})	55.74	7.51

The population consisted of active men aged between 18 and 35 years old with no declared neurological or motor deficits. Participants were recruited through posters and communication among well-trained physical students and multisport practitioners. Volunteers were included in the experimental group and remunerated for their participation. This study was approved by the Léon Bérard Centre's Research and Ethics Committee under the number A 13–160.

In addition, to take into account the types of sports practiced by the subjects, we divided them into two categories: sports with endurance (END) characteristics (triathlon, running, cycling and trail running) and those without (climbing, volleyball, basketball, judo, water polo, etc.). We had 22 athletes in the NONEND group and 20 in the END group.

2.2. Participants Recruitment and Ethical Approval

Each participant completed an IET. The purpose of the IET was to assess maximal aerobic power (MAP) and maximal oxygen consumption ($\dot{V}O_2max$).

Prior to the test, a standardized warm-up allowed participants to familiarize themselves with the protocol and equipment. Each participant was asked to pedal constantly for 8 min: 2 min and 45 s at 50 W, and 5 min and 15 s, including six stages of 15 s each from 90 to 240 W (increasing by 30 W per stage), interspersed with 45 s intervals at 50 W basal power output. During the 5 min recovery period that followed, the participants were fully equipped before beginning the IET. This test was preceded by a 30 s period at 50 W before performing an incremental test until exhaustion. The test itself began at the power of 90 W and consisted of a series of two-minute increments of 30 W, with participants pedaling at their own frequency. No information on power or time was given during the test.

No verbal encouragement was given during the test. The experimental session is presented in Figure 1.

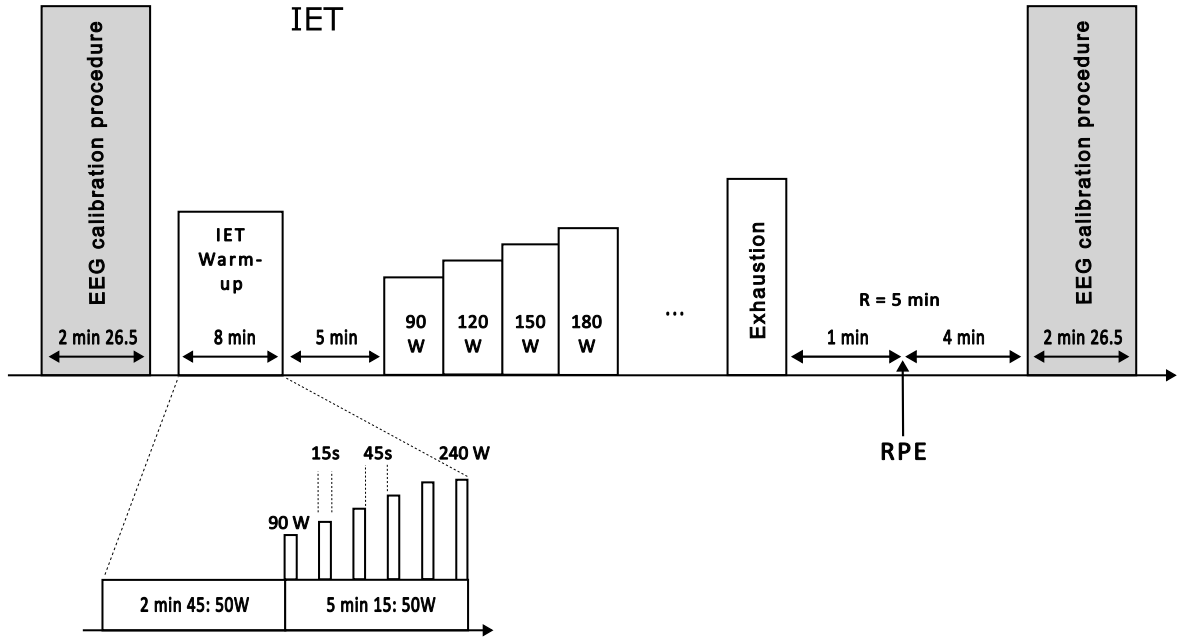


Figure 1. Summary of experimental session. The session began with a brief EEG calibration, followed by an 8 min warm-up. After a 5 min recovery period, the IET was performed until exhaustion. RPE test was then performed during the next 5 min of recovery, before the final EEG calibration procedure. EEG: electroencephalogram, IET: incremental exercise test, and RPE: rate of perceived exertion.

2.3. Experimental Design

Participants were seated in a chair. Using an abrasive cream (Nuprep®, Weaver and Company, Aurora, CO, USA) and a cotton swab, the skin was rubbed at the location of the reference and ground electrodes. This operation removed dead cells, impurities, and excess sebum to improve conductivity. Additionally, the forehead, scalp, and hair were degreased with a compress soaked in 70% alcohol [52]. They were then fitted with a Polar® heart rate belt, a gas mask, and an EEG headset. The EEG electrodes were positioned with conductive gel between the scalp and the electrodes to improve contact between the skin and the sensor. Subjects were then seated in a semi-recumbent position on a cyclo-ergometer, as shown in Figure 2.

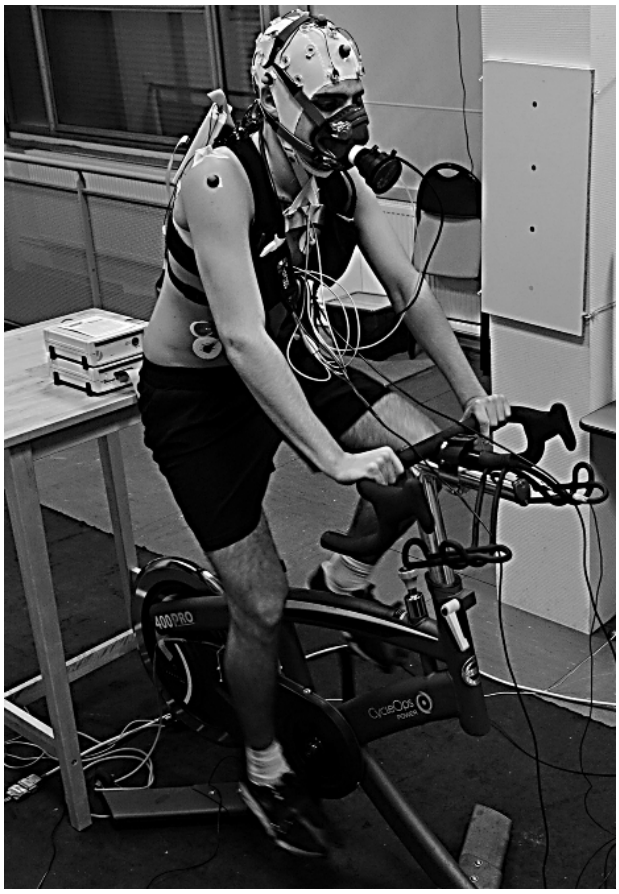


Figure 2. Positioning of sensors and participants on the ergocycle.

In accordance with traditional recommendations [53,54], the electrodermal sensors were placed on the second phalanx of the second and third fingers of the non-dominant hand (or on the third phalanx, in case of frequent potential contact between the sensors and the environment). A conductive gel (Teca, ref. 822-201210) was applied between the sensors and the skin to improve contact after cleansing the skin with a mixture of alcohol and ether. The electrodes were then firmly strapped to the fingers using hypoallergenic adhesive tape. Finally, six 3D kinematic markers were placed on the head and shoulder (see Figure 2).

The impedance of the EEG electrodes was then checked, allowing the conductive EEG gel time to warm up to body temperature. The target impedance values were between 1 and 5 kΩ. If the impedance values were higher than 5 kΩ, conductive gel was added until the impedance reached the required values. At this point, the EEG calibration procedure began, as shown in Figure 3, and proceeded in the following sequence: 30 s with eyes open, 30 s with eyes closed, 15 s of eye blink, 15 s of eye movement, and 12.5 s of head movement alone in the four directions (left, right, up, and down). A 7.5 s pause was observed between each test sequence. The experimental EEG calibration procedure was carried out using Presentation® software (version 18.1, www.neurobs.com (accessed on 19 June 2024)) and presented on a computer in front of the subject. Participants were asked to look straight ahead and to remain motionless during the procedure, except for what they were asked to do.

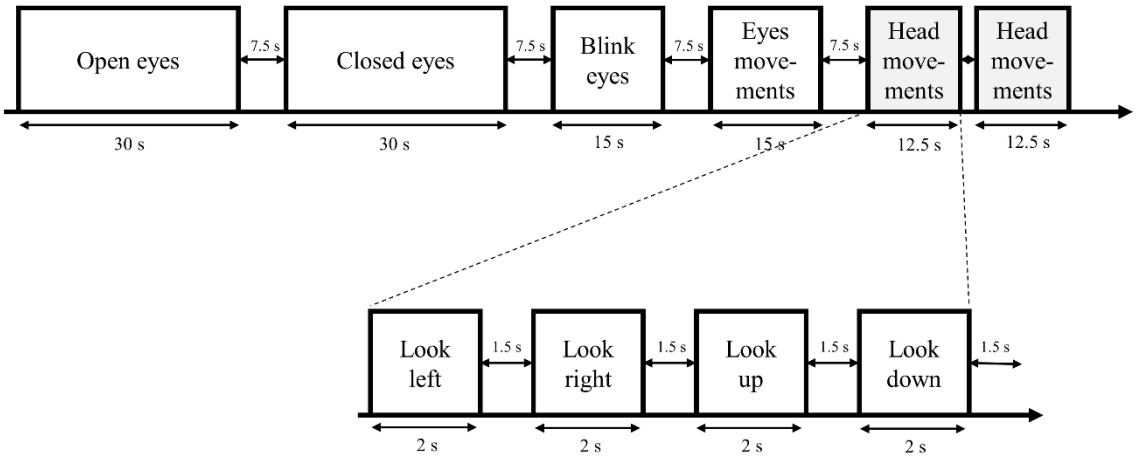


Figure 3. EEG calibration procedure. The whole procedure takes approximately 2′30″. After 30 s of open eyes followed by 30 s of closed eyes, the procedure requires 15 s of blink eyes and 15 s of eyes movement before 2 sets of 12.5 s of demanding head movements.

After remaining static during the EEG calibration sequence, each participant warmed up for 8 min (see Figure 1). They were then fitted with a nafion/permapure sampling tube connected to a turbine for measurements of pulmonary gas exchange. Each subject then performed the physical test described above. The participants were asked to remain seated on the saddle in order to limit head and upper body movements as much as possible. After each test and one minute's rest, each participant was asked to complete a perceived exertion rating scale (see below). After a 5 min rest, the EEG calibration procedure (Figure 3) was again performed, along with the impedance check.

Rating of Perceived Exertion (RPE) Scale

We asked each participant to rate the perceived exertion on a scale of 6 to 20 at the end of the IET. A score of 6 corresponds to rest and is closely correlated to a resting heart rate value, while 20/20 corresponds to maximal effort with the highest heart rate values [55].

2.4. Measurements

During the test, six apparatus recorded measurements throughout the exercise. Descriptions of each device are presented here, along with the relevant data recorded.

2.4.1. Ergocycle Data

We used the CycleOps 400 Pro Indoor Cycle (Saris Cycling Group, Inc., 5253 Verona Road, Madison, WI 53711, USA) with the CycleOps Joule 3.0 (Saris Cycling Group, Inc.) computer. The Joule 3.0 CPU uses ANT+ technology to communicate wirelessly with the bike's sensors (i.e., the PowerTap power meter in the rear flywheel, speed sensor, cadence sensor, and heart rate strap sensor). The warm-up and the IET have been programmed in advance. This ergocycle makes it possible to adjust the power output regardless of the pedaling cadence. All data were stored on the Joule 3.0 CPU and downloaded to a computer running Power agent software (version 7.8.28) (Saris Cycling Group, Inc.). Power (W), torque (Nm), speed (km/h), cadence (rpm), and heart rate (bpm) were recorded and stored at a sampling rate of 1 Hz.

2.4.2. Electroencephalography Measurements

EEG was recorded using a 32-channel ActiCap system (Brain Products, Gilching, Germany), which combines active electrodes based on high-quality Ag/AgCl sensors with the application of a conductive gel to lower impedances. Ten sensors were used for the measurements. We used the following sites from the extended 10–10 system: Fp1, Fp2, Fz, C3, Cz, C4, Pz, O1, Oz, O2. The ground electrode was placed on the lateral third

of the right scapula spine. All electrodes were referenced to an electrode placed on the right mastoid, and impedances were kept below 5 kΩ for all sensors. Analog signals were amplified (analog band-pass filter 0.016 Hz–1000 Hz) with a BrainAmp amplifier (Brain Products, Germany) and digitized at a frequency of 5000 Hz. EEG data were downsampled to 1000 Hz (with a 400 Hz anti-aliasing filter) and recorded using the Brain Vision Recorder software (version 1.20.0601, Brain Products, Gilching, Germany).

2.4.3. Heart Rate (HR) Measurements

Heart rate was measured in two different ways. Firstly, it was measured using a heart rate belt (Polar®) and synchronized with the gas measurements. Secondly, it was measured using a three-channel electrocardiogram (ECG) and synchronized with the electrodermal apparatus. The time of occurrence of the R-waves could thus be accurately determined. The D2 derivation signal (the interval between two consecutive ECG R-waves) was electronically processed and delivered in the form of instantaneous heart rate. In the case of missed ECG R-waves or false detection due to artifacts, HR could be estimated offline using an algorithm that iteratively replaced changes in IHR above a threshold of 10 beat per minute (bpm) with interpolated values. The interpolation was calculated between pairs of values below the threshold. The new signal, free of artifact, was then resampled. The smallest appreciable variation was 0.5 bpm, and the calibrated scale ranged from zero to 200 bpm. The IHR signal was then extracted directly from the ECG at the sensors. The IHR was therefore treated as an analog signal. Data acquisition was performed at 10 Hz on this analog signal.

2.4.4. Gas Measurements

O_2 and CO_2 concentrations during the test were measured using a Metamax® 3B mobile gas analyzer (Cortex Biophysik GmbH, Leipzig, Germany). Breath-by-breath data on respiratory volume and gas concentrations were sent in real-time by telemetry to a PC. Metasoft® software (version 3.9.9 SR5) calculated ventilation rate ($\dot{V}E$), oxygen consumption ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and synchronized all gas data with heart rate. The system ran for at least 30 min and was calibrated before each test in accordance with the manufacturer's recommendations.

As the ergocycle used in this study could not receive any analog or digital signal, we used its pedaling signal, as well as the pedaling signal provided by the trigger, to synchronize the ergocycle's data with the others (Figure 4).

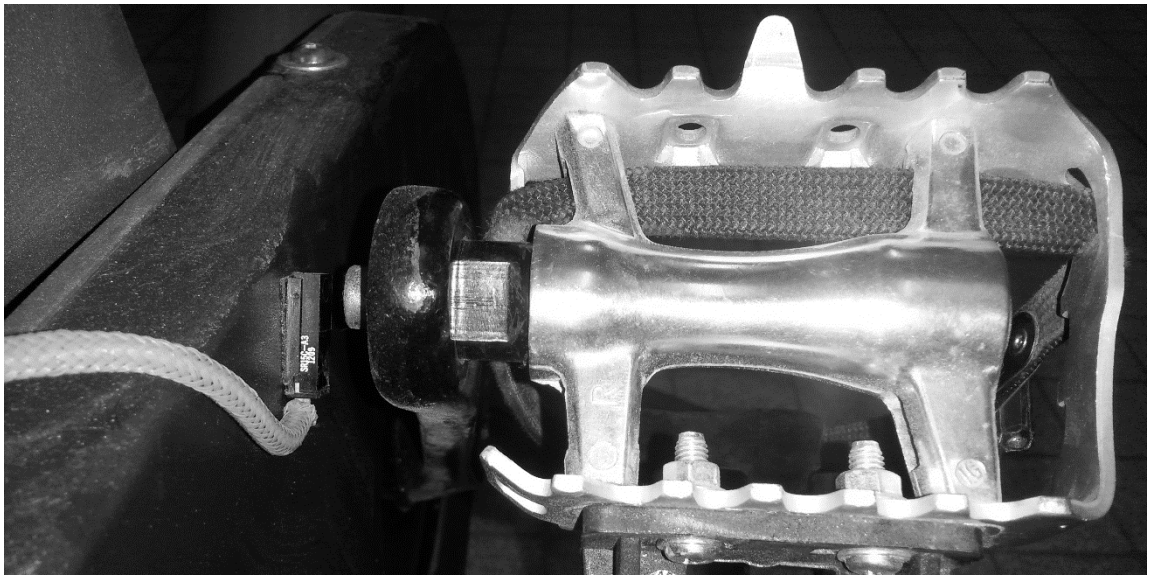


Figure 4. Magnet attached to the pedal and Hall-effect sensor attached to the ergocycle frame.

Similarly, as the gas analyzer used in this study had no possible signal input, we used its ability to record heart rate to synchronize it with the electrodermal activity (EDA) device, which also provided a heart rate measurement.

In summary, Figure 5 shows the different devices and how they are synchronized with each other.

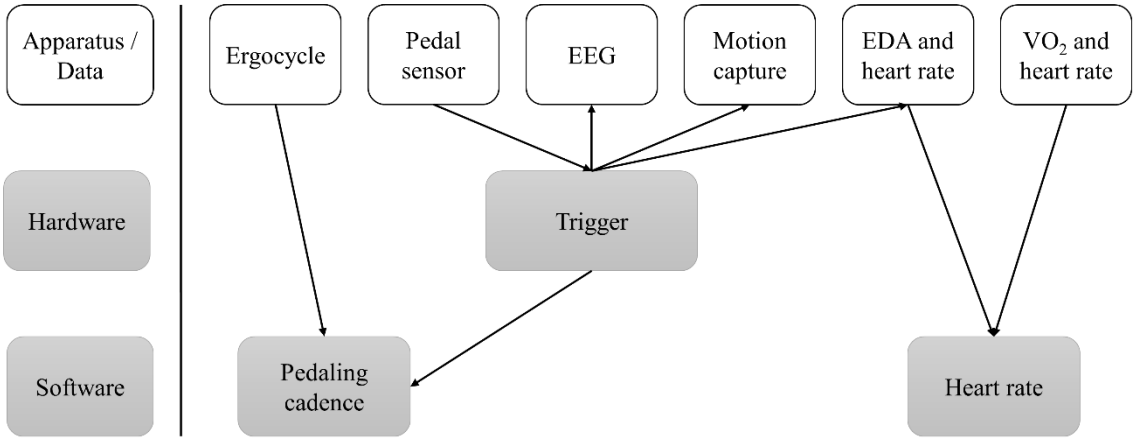


Figure 5. Device and data synchronization strategies (hardware and software). EEG: electroencephalogram, EDA: electrodermal activity, and $\dot{V}O_2$: oxygen consumption.

2.4.5. Determination of the $\dot{V}O_2$max Plateau

Following the recommendations of Niemeyer and colleagues in the major review of the oxygen uptake plateau as a "frequently misunderstood phenomenon" [5], we used fairly wide sampling intervals (i.e., the $\dot{V}O_2$pl was determined from more than the final 30 W or 60 s) and a cut-off that was set at approximately half the expected increase in $\dot{V}O_2$ in the submaximal intensity range. Additionally, as recommended by Poole and colleagues [14], we did not use the "so-called" secondary criteria as a maximal value of respiratory exchange ratio (RER) $\geq$ 1.1, maximum HR value (HRmax) greater than 95% of the maximum value predicted for age (220-age), and the end-exercise blood lactate criterion greater than 8.0 mmol/L, although we only checked that all subjects had achieved these at the end of the IET at the same time as we asked them for their RPE value. If subjects did not satisfy the $\dot{V}O_2$ criteria but satisfied the secondary ones, we considered the higher $\dot{V}O_2$ value was a $\dot{V}O_2$peak. The workload eliciting the RCP was determined using the criteria of an increase in both the VE/$\dot{V}O_2$ and VE/$\dot{V}O_2$ and a decrease in end-tidal carbon dioxide pressure ($PetCO_2$) [56]. To determine RCP, the values of the gas-exchange variables were averaged for every 1 min period and plotted against workload. For statistical comparisons between groups (see below), RCP was expressed as the mean value of %$\dot{V}O_2$max for the corresponding 1 min interval. Two experienced independent observers detected RCP. In case of disagreement, we sought the opinion of a third investigator.

2.5. Signal Processing

EEG: Data Reduction Procedures for Artifact Correction and Removal

We paid particular attention to preventing and/or limiting artifacts due to muscle contraction, eye, or body movement [57]. The use of active gel EEG electrodes was likely to overcome this problem thanks to an integrated noise subtraction circuit, thus improving the reliability of data collection [32]. We rejected abrupt variations in the signal by analyzing it using a 2 s time window. The resulting EEG signal shows a noise level (Figure 6) that:

- Increases systematically towards the end of the recording and the highest effort.
- Is higher on the occipital derivation, probably due to muscle contraction.
- Is kept to an acceptable level (approximately 20 dB at 50 Hz).

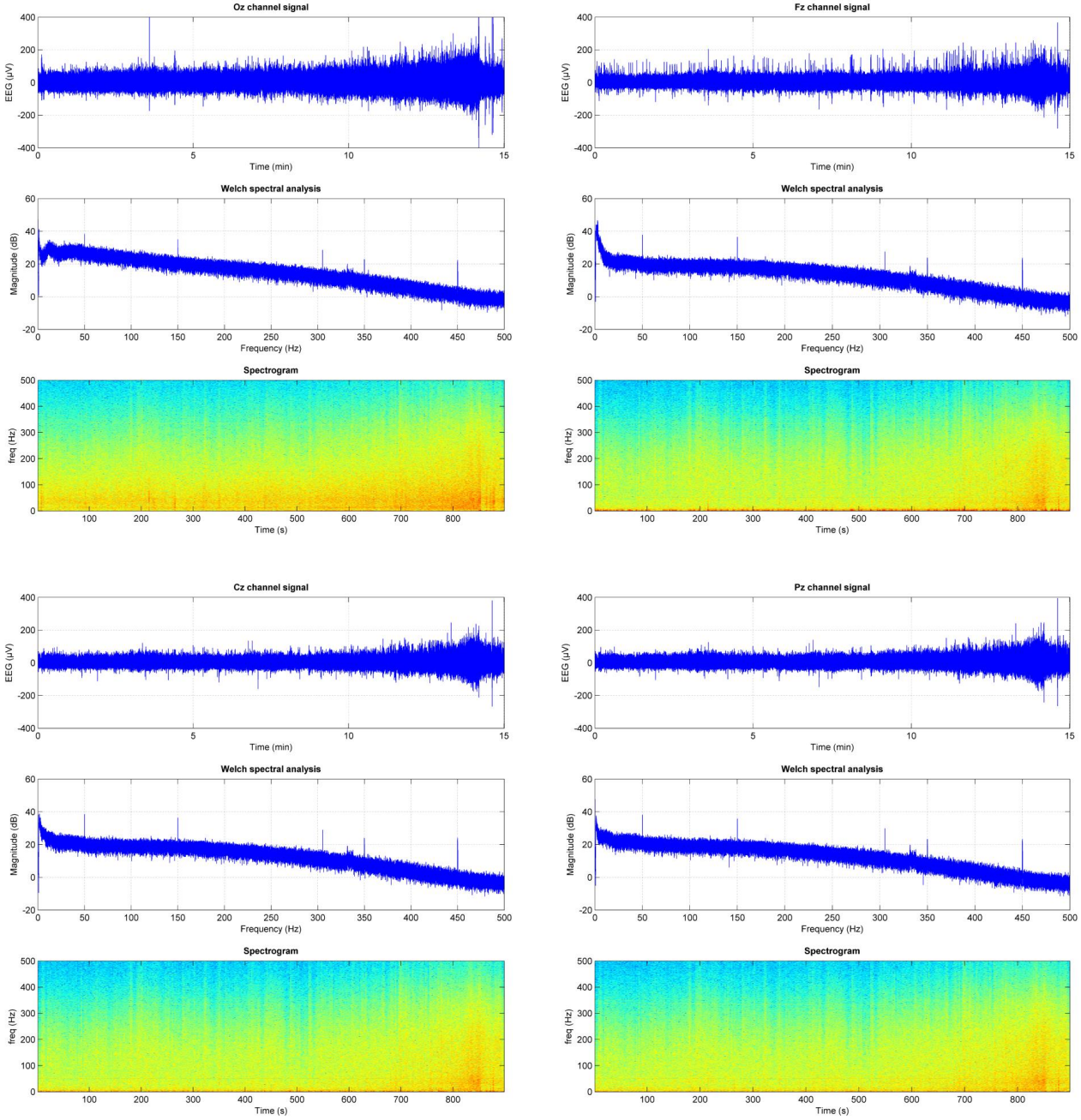


Figure 6. Typical raw traces obtained during the incremental exercise test for Oz, Fz, Cz and Pz channel signals with the raw signal, Welch spectral analysis and spectrogram for each channel. In the spectrogram, cooler colors (blue and green) represent low power and warmer colors (white, red and yellow) represent high power. EEG: electroencephalogram; freq: frequency.

It also shows the presence of residual artifacts. Eye blinks are visible in the temporal signal at the frontal site. Some artifacts are found in the lower frequency bands where EEG activity is expected to occur, but at an amplitude that does not generate signal saturation. These artifacts will present a challenge to subsequent EEG analysis, but can be subject to artifact rejection procedures. A specific artifact rejection method has been developed [58].

2.6. Statistics

A two-way ANOVA was used to analyze changes in the mean of a quantitative variable as a function of the levels of two categorical variables (END and NONEND, PLAT and NONPLAT). More specifically, we investigated the main effect A: the average difference in

physiological and neurophysiological responses due to variations in the first independent variable, i.e., PLAT vs. NONPLAT factor, and for the main effect B: the average difference in the dependent variable due to variations in the second independent variable, i.e., the END vs. NONEND sports practice. We also examined the interaction effect in order to determine whether the effect of PLAT compared with NONPLAT depended on the level of the END vs. NONEND variable. In other words, we wanted to check whether the combined effect of both variables was different from what we expected on the basis of their individual effects. We therefore measured the impact of achieving $\dot{V}O_2$max NONPLAT and PLAT on the ratio of EEG power to $\dot{V}O_2$ profile during the IET for θ, α, β, α/β ratio, RPE, $\dot{V}O_2$max, HRmax, and RCP (%$\dot{V}O_2$max). We also proceeded in the same manner for the NONEND and END factors. To achieve this, we used a two-way ANOVA (XLSTAT 2023.2.0, Paris, France).

In addition, we used the Pearson product-moment correlation coefficient to measure the strength of the linear relationship between the EEG response (α, β, α/β ratio) and $\dot{V}O_2$. If the relationship between the variables is not linear, the correlation coefficient does not correctly represent the strength of the relationship between the variables. We have considered the value alpha < 0.05 for the significance level, i.e., the probability that you will make the mistake of rejecting the null hypothesis when it is true. If the *p* value is greater than alpha, you accept the null hypothesis. If it is less than alpha, you reject the null hypothesis.

3. Results

3.1. Occurrence of $\dot{V}O_2$pl in the Whole Group (n = 42)

All subjects completed the test. The results are presented in Table 2.

A $\dot{V}O_2$pl was observed in twenty-two subjects (52%) (Figure 7, example of a $\dot{V}O_2$pl), while the remaining twenty subjects achieved a $\dot{V}O_2$peak and met the secondary $\dot{V}O_2$max criterion. It should be noted that the RPE did not reach maximal values corresponding to very hard (17/20), since the average value for the whole group was only 16.8 ± 1.5 (Table 2). On the other hand, there was no difference between the NONPLAT and PLAT groups or NONEND and END groups (Table 3).

Table 2. Physiological, mechanical and RPE results for the IET.

Variable	Mean	SD	Range
$\dot{V}O_2$max (mL·min^{-1}·kg^{-1})	55.74	7.51	40.0
Maximal Aerobic Power (W)	273.78	42.49	180.0
Relative Maximal Aerobic Power (W/kg)	3.74	0.67	3.4
HRmax (bpm)	188.52	9.83	45.0
Time (s)	967.44	162.52	713.0
RPE	16.79	1.50	5.0

SD: standard deviation, RPE: rating of perceived exertion, and $\dot{V}O_2$max: maximal oxygen consumption.

Table 3. Effects of NONPLAT or PLAT and NONEND or END groups on characteristics and physiological variables.

	n	$\dot{V}O_2$max (mL·min^{-1}·kg^{-1})	Age (Years)	Height (cm)	Training/Week (Hour)	Final RPE	RCP (%$\dot{V}O_2$max)
NONEND	*n* = 22	51.77 ± 6.41	24.23 ± 4.34	181.95 ± 8.00	6.95 ± 4.74	16.55 ± 1.72	73.97 ± 11.89
END	*n* = 20	60.10 ± 6.16	27.55 ± 5.04	179.00 ± 4.87	8.05 ± 4.75	17.08 ± 3.99	77.02 ± 7.52
F value		−4.10	−2.25	1.08	−0.91	−1.04	−0.557
p value		**<0.001**	**0.03**	0.285	0.368	0.305	0.581
NONPLAT	*n* = 20	55.00 ± 5.64	25.85 ± 5.17	181.75 ± 6.84	8.15 ± 5.82	16.66 ± 4.02	73.88 ± 11.08
PLAT	*n* = 22	56.41 ± 8.96	25.77 ± 4.81	179.45 ± 6.70	6.86 ± 3.45	16.91 ± 1.47	76.82 ± 9.05
F value		0.353	0.684	0.665	1.149	−0.271	−1.11
p value		0.72	0.498	0.510	0.258	0.788	0.273

Values in bold indicate a statistically significant *p*-value (α = 0.05). RCP: respiratory compensation threshold, RPE: rating of perceived exertion, $\dot{V}O_2$max: maximal oxygen consumption, NONEND: non-endurance group, and END: endurance group.

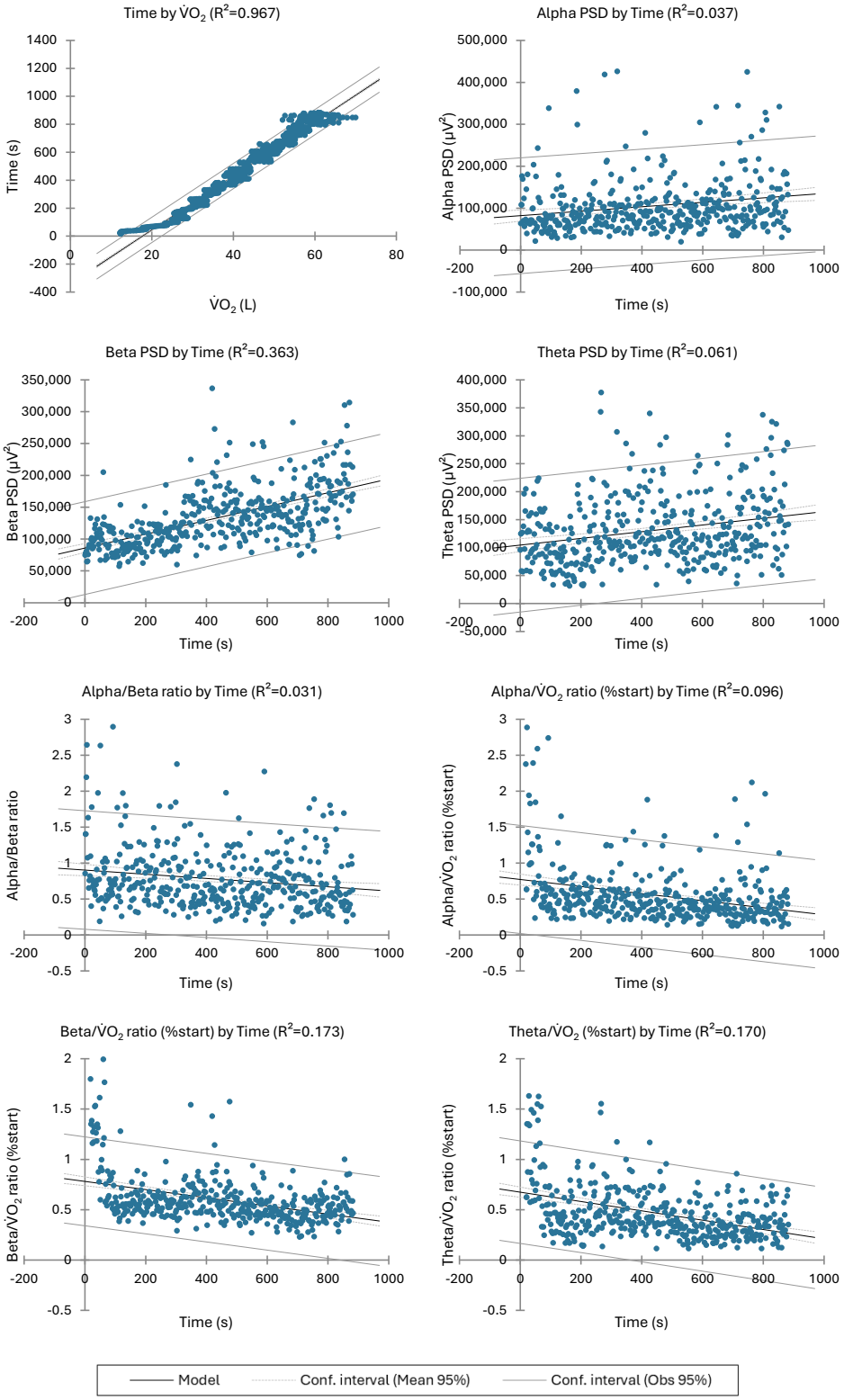


Figure 7. Linear regression of various physiological parameters by time for the subject 940 reaching a $\dot{V}O_2$pl. Subfigures include $\dot{V}O_2$, theta power, alpha power, beta power, alpha/beta power ratio, alpha/$\dot{V}O_2$ as a percentage of starting alpha/$\dot{V}O_2$ power, beta/$\dot{V}O_2$ as a percentage of starting beta/$\dot{V}O_2$ power, and theta/$\dot{V}O_2$ power as a percentage of starting theta/$\dot{V}O_2$ power. PSD: power spectral density.

3.2. Difference in Physiological and Training Parameters between the NONPLAT and PLAT Groups or NONEND and END Ones

Table 3 reports the non-significant values of $\dot{V}O_2$max, training volume, height, final RPE, and fractional use of $\dot{V}O_2$max at the RCP. The only significant difference between plateau or endurance practice criteria was that the endurance group had a higher $\dot{V}O_2$max ($p = 0.0002$) and was older ($p = 0.03$). Training volume did not differ significantly between the groups.

3.3. EEG Responses vs. $\dot{V}O_2$ Increase, between the NONPLAT and PLAT Groups or NONEND and END Ones during the IET

In all subjects, we observed a decrease in the α/β ratio and an increase in theta and beta (presented as percentage of the start value in Table 4).

Table 4. Effects of NONPLAT or PLAT and NONEND or END groups on EEG variables. Theta and beta values are expressed as a percentage of the starting value of the IET.

		Alpha/Beta Ratio	Theta Increase (%start)	Beta Increase (%start)
NONEND	$n = 22$	-20.30 ± 12.93	20.39 ± 16.43	40.06 ± 19.97
END	$n = 20$	-15.74 ± 11.93	20.24 ± 16.43	47.00 ± 16.14
F value		1.36	0.01	1.33
p value		0.250	0.907	0.256
NONPLAT	$n = 20$	-18.58 ± 12.71	18.29 ± 13.31	44.26 ± 18.59
PLAT	$n = 22$	-17.93 ± 12.67	22.25 ± 18.65	42.34 ± 18.93
F value		<0.001	0.74	0.08
p value		0.988	0.395	0.778

NONEND: non-endurance group; END: endurance group.

Figure 7 (and Table 5) shows an example of the EEG response during the IET in one subject (id 940) who was in the PLAT and NONEND groups. These EEG responses were the same for all subjects, with the exception of the alpha response, which exhibited some variability. Specifically, it increased in 27 of 42 subjects and decreased in the remaining 15. However, the frequency distribution of the alpha value tendency did not differ significantly from the expected frequencies (Table 6).

Table 5. Summary table of analysis of variance for $\dot{V}O_2$, theta power, alpha power, beta power, alpha power/beta power ratio, alpha/$\dot{V}O_2$ as a percentage of initial alpha/$\dot{V}O_2$ power, beta/$\dot{V}O_2$ as a percentage of initial beta/$\dot{V}O_2$ power, and theta/$\dot{V}O_2$ power as a percentage of initial theta/$\dot{V}O_2$ power.

	$\dot{V}O_2$	Alpha PSD	Beta PSD	Theta PSD	Alpha/Beta Ratio	Alpha/$\dot{V}O_2$	Beta/$\dot{V}O_2$	Theta/$\dot{V}O_2$
R^2	0.967	0.037	0.363	0.061	0.031	0.096	0.173	0.170
F	25,011.7	16.0	238.1	27.0	13.1	42.7	85.6	84.0
Pr > F	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

PSD: power spectral density; $\dot{V}O_2$: maximal oxygen consumption.

Nevertheless, although not significant, given the alpha threshold of 5% against which we compare p values ($p = 0.07$), fewer END subjects show a decrease in alpha power compared to the NONEND group. However, when we focused on the ratio of alpha power expressed as a percentage of the starting value to $\dot{V}O_2$ as a percentage of the starting value, it decreases in all subjects, indicating a "depletion" of alpha power compared to the metabolic demand, as was observed in all subjects for the other EEG power bands.

In addition, there was also no impact of the distribution of these different tendencies between groups for NONPLAT and PLAT subjects (Table 7) and the increase or decrease tendency of cadence, EEG $\theta/\dot{V}O_2$, EEG $\alpha/\dot{V}O_2$, EEG $\beta/\dot{V}O_2$, and α/β ratio (Table 8).

Table 6. Frequency distribution of alpha value trend in subjects.

	Positive Alpha Tendency	Negative Alpha Tendency	*p* Value
NONEND	12	10	0.07
END	15	5	
NOPLAT	14	6	0.75
PLAT	12	10	

NONEND: non-endurance group, END: endurance group, NOPLAT: non-plateau group, and PLAT: plateau group.

Table 7. Effects of NONPLAT or PLAT and NONEND or END groups on alpha power expressed as a percentage of alpha power at the start of the IET.

Chi-Square (Observed Value)	Chi-Square (Critical Value)	DF	*p* Value	Alpha
3.663	7.815	3	0.300	0.05

Table 8. Chi-square test for cadence, EEG $\beta/\dot{V}O_2$, EEG $\theta/\dot{V}O_2$, EEG $\alpha/\dot{V}O_2$ and α/β ratio between the NONPLAT (n = 22) and PLAT (n = 20) groups.

	Cadence	EEG $\theta/\dot{V}O_2$	EEG $\alpha/\dot{V}O_2$	EEG $\beta/\dot{V}O_2$	α/β Ratio	All
Chi-square (Observed value)	0.005	0.225	0.431	0.558	0.288	7.61
Chi-square (Critical value)	3.84	3.85	3.86	3.84	3.87	16.9
p value	0.945	0.636	0.512	0.455	0.591	0.57

EEG: electroencephalogram, α: alpha frequency band, β: beta frequency band, and θ: theta frequency band.

4. Discussion

The main aim of this study was to compare the EEG responses during an incremental exercise test in two groups of subjects who had achieved a $\dot{V}O_2$pl or not.

The debate around the $\dot{V}O_2$pl and its cause remains a long story of exercise physiology for nearly half a century, and as Noakes [59] states, "it is time to move beyond a brainless exercise physiology". We hypothesize that the difference between athletes who reached the plateau of their $\dot{V}O_2$max and those who did not could be present in different EEG characteristics and in EEG/$\dot{V}O_2$ ratios. Our main results showed no incidence of the $\dot{V}O_2$pl or not, nor of endurance or non-endurance practice, on EEG activity during IET. Regardless of group, all subjects showed an increase in beta and theta band power, while alpha band power was less uniform (half increasing and half decreasing, independent of group membership).

However, when we plotted the EEG band power against oxygen power demand, both relative to the start value, all subjects showed a decrease in alpha, beta, and theta/$\dot{V}O_2$ ratios during IET. Therefore, even if the brain is not the limiting factor of $\dot{V}O_2$max or responsible for the attainment of $\dot{V}O_2$pl or not, these results, given the relationship between EEG responses and oxygen demand, could constitute a new marker of a progressive "depletion" of EEG power capacity. Considering each of these elements, it may be recalled that at rest, alpha waves are generally more observed when a person is in a relaxed mental state [60]. During exercise, an increase in alpha activity may indicate increased attention or alertness, as the brain focuses on the task at hand [61]. However, an excessive reduction in alpha activity during exercise may reflect a large effort, yielding mental fatigue or decrease cognitive performance [62]. Beta waves are associated with active concentration, problem solving, and alertness [63]. During exercise, increased beta wave activity may reflect heightened cognitive engagement and concentration, particularly during tasks requiring attention and coordination [64,65]. Theta waves are linked to deep relaxation, meditation, and drowsiness [66]. During exercise, a decrease in theta

wave activity can occur when a person is overexerted, which can lead to difficulties in maintaining precise sensorimotor control and monitoring sensory inputs due to reduced executive functions or decreased attention [67]. Overall, beyond EEG changes in the alpha, beta, and theta bands during exercise, the increases observed relative to that of $\dot{V}O_2$ highlight the importance of including central measures in our physical activity studies. This was the goal of this interdisciplinary approach using physiology, neurophysiology and biomechanics synchronizing all measurements during exercise performed at free cadence.

- Difference in maximal value of $\dot{V}O_2$, heart rate, RPE, and training parameters between the NONPLAT and PLAT groups or NONEND and END ones.

The occurrence of $\dot{V}O_2$pl was not dependent on specialty and therefore on maximum $\dot{V}O_2$, given that, unsurprisingly, the END group had a higher $\dot{V}O_2$max than the NONEND group. Thus, given that the END and NONEND athletes were equally distributed in the NONPLAT and PLAT groups, we can consider that specialty does not influence the occurrence of $\dot{V}O_2$pl. Since this factor (specialty) also has no impact on RCP, we can assume that they did not have contract a significant oxygen deficit before reaching $\dot{V}O_2$max (with or without plateau).

- The occurrence of $\dot{V}O_2$pl

The "plateau phenomenon", described by Mitchell and Blomqvist in 1971 [68], was observed during 3 consecutive workloads. Before them, in 1955, Taylor and colleagues introduced a criterion for identifying a $\dot{V}O_2$pl during exercise [69]. This threshold was set at $\leq$150 mL/min (or $\leq$2.1 mL·min^{-1}·kg^{-1}) based on the average increase in subjects' $\dot{V}O_2$ over incremental exercise increments. However, this method has been criticized [5,11]. Moreover, according to the positioning of eminent colleagues [4] on this issue, we did not consider the so-called "secondary" criteria (heart rate (HR) $\leq$10 beats/min or $\leq$5% of the maximum predicted by age (220-age), blood lactate concentration $\geq$8 mM, or respiratory exchange ratio (RER) >1.00, 1.10, or 1.15). Thus, when we obtain these criteria without an individual reaching a plateau, the "$\dot{V}O_2$peak" referred to the highest $\dot{V}O_2$ reached during a graded exercise test, as has been done in most research on maximal exercise tests in children for whom there was some difficulty in demonstrating a $\dot{V}O_2$pl [70]. Thus, in this study, to compare the EEG response during IET as a function of the occurrence of a $\dot{V}O_2$pl, this was defined as less than half the expected increase. According to this definition, we observed a $\dot{V}O_2$pl occurrence in 52.6% of our subjects, in accordance with previous studies [4,5,9,11,18,19,71,72].

- RPE response between the groups

Hill's model emphasizes the concept of a "critical metabolic state" in which metabolite accumulation reaches a threshold level, triggering fatigue and necessitating a reduction in exercise intensity to avoid metabolic imbalance and potential damage to muscle tissue. In essence, Hill proposed that fatigue is a protective mechanism that prevents excessive muscular strain and maintains physiological homeostasis [1,73,74]. The central governor theory challenged (or we might say, achieved) Hill's peripheral model of fatigue by emphasizing the role of the brain as a central regulator of exercise performance. The founders and protagonists of this "central governor theory" argue that while peripheral factors, such as muscle fatigue and metabolic stress, undoubtedly contribute to fatigue, the brain's role in pacing and regulating exercise intensity is paramount [75,76]. They suggest that the brain integrates sensory feedback from the muscles, cardiovascular system, and other physiological systems to modulate exercise effort and prevent catastrophic failure [59,71]. Here, we used perceived exertion to measure the subjective experience of intensity, stress, discomfort, and/or fatigue during physical activity. The RPE scale, first introduced in 1970 and subsequently refined by Borg [77], remains the predominant tool for assessing perceived exertion in adults [78]. Some studies suggest an even stronger correlation between RPE and $\dot{V}O_2$ [79,80]. The widespread adoption of RPE to assess exercise intensity may be explained by the ability of human beings to perceive effort, which derives from continuous

use of a well-developed sensory system. During exercise, individuals are aware of their overall effort and can discern the location of the effort, allowing them to gauge the intensity of the exercise and estimate their endurance at a given level [81,82]. The experience accumulated with different intensities of exercise enables individuals to numerically evaluate or at least classify the intensity of exercise via the RPE scale. Whatever the group (END or NONEND; PLAT or NONPLAT), the subjects rated their RPE just below 17/20, i.e., the beginning of what they perceived as "very hard". We can therefore consider that the RPE does not play a role in the difference in potential EEG response during the IET. However, Samuele Marcora's theory [75] postulates that the perception of effort during exercise may be independent of afferent feedback from the muscles, heart, and lungs. He argues that the prevailing notion attributing a substantial influence to afferent feedback on the perception of effort may result of an overly broad framework. Marcora emphasizes the role of hedonicity in overall perception and argues for a narrower definition of exertion, aligned with the descriptors of Borg's RPE scale. He suggests that while sensory mechanisms may influence the perception of effort, experimental studies have dissociated the perception of effort from metabolic stress, indicating that the brain primarily generates the sensation of effort, with limited influence from afferent feedback.

- EEG responses between the NONPLAT and PLAT groups or NONEND and END ones during the IET

Therefore, there is a consensus that an individual's exercise performance is modulated by feedback from various physiological systems under the control of the brain. This is a different debate to that of the factors limiting $\dot{V}O_2max$ and its definition and here, by examining the EEG response as a function of the occurrence of $\dot{V}O_2pl$, we showed that the EEG response was affected neither by plateau nor by sports specialty and hence, the value of $\dot{V}O_2max$. Independently of the occurrence of a $\dot{V}O_2pl$, we found an increase in theta and beta power, while alpha power decreased or increased. These results regarding the increase in beta and theta frequency band and alpha/beta ratio, are in accordance with those of previous studies [83]. In their examination on EEG during exercise, Hosang and colleagues observed a predominant increase in alpha and beta activity following high-intensity exercise compared to low or moderate intensity exercise sessions [83]. Previous studies have noted that heat stress induced by exhaustive exercise can increase cortical activity, which could explain the link between exercise intensity and changes in alpha, beta, and delta activity [84–87]. Another plausible explanation for the increase in beta activity, particularly in fronto–central regions, is its association with high levels of psychomotor arousal [84] and increased cortical activation during voluntary movements [88–90]. Increased theta activity has also been associated with the processing of novel information, suggesting that the theta results observed may be related to the control and regulation of attentional resources [91,92].

Emerging evidence suggests that the onset of fatigue leading to exercise cessation is associated with afferent feedback, a neural factor regulated and interpreted by the brain [93]. This feedback is linked to sensory information detecting unpleasant stimuli such as lactate accumulation in active muscles, fatigue of peripheral locomotor muscle or an increase in central temperature, leading to a cerebral response. Afferent information from the periphery is transmitted to the prefrontal cortex, where it is interpreted and influences the decision to stop exercise. EEG has been proposed as a practical, non-invasive approach to gathering valuable information about changes in brain activity during rest and exercise [34]. This study attempted to provide information on brain regulations to exhaustion as a function of their respective limiting factors [31,33,34]. In both cases, our multimodal device may allow fatigue to be monitored by several methods, to study the interactions between the central nervous system, the autonomic nervous system, and respiratory exchanges during acute exercise, which may provide information on exercise tolerance and regulation [25,26,49,50]. Here, we attempted a multimodal approach providing different indicators of cortical activity changes that were synchronized with autonomic nervous system, gas exchanges, heart rate and behavioral performance while controlling body movements during an IET

and comparing the EEG/$\dot{V}O_2$ profile according to the occurrence or non-occurrence of $\dot{V}O_2$pl.

- Impact of the cadence on the EEG responses between the NONPLAT and PLAT groups or NONEND and END ones during the IET

As cadence has an impact on EEG and response during exercise [43,94,95], we allowed the participant to freely choose the pedaling frequency associated with a fixed power output. This should facilitate exercise, particularly when participants were not accustomed to pedaling on a cyclo-ergometer. In addition, changes in pedaling frequency can indicate the onset of fatigue or disengagement and can be objectively confirmed by physiological measures. Recording body movements should help to control the quality of EEG data by providing information that helps to distinguish the signal from movement noise. Thanks to the quality of the recordings, and even with a reduced number of electrodes (10 compared with the usual 20 to 64), a wide range of brain areas was covered. We were thus able to analyze the four frequency bands usually studied in sports science in the frontal, parietal and central regions of the brain: theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and low gamma (30–50 Hz) [31,33]. As Bailey and colleagues suggest, EEG activity from previous research is difficult to compare due to specific differences in exercise protocol and apparatus [31]. For example, the site-specific density of electrical activity in the motor cortex was found to increase with exercise intensity until exhaustion [32]. Previously reported changes in EEG response to exercise showed that EEG activity varied during incremental or constant load exercise tests across all bandwidths [31,33,34]. Furthermore, it has been found that alpha activity in the motor cortex is not fully activated and is maintained during exercise exhaustion [50]. In contrast, alpha activity in the frontal cortex decreases from the second ventilatory threshold until exhaustion [33]. The frontal cortex could therefore play a central role in the cessation of exercise because of the changes it undergoes during high levels of physical exertion [50]. The precise cause of the effects of high-intensity exercise on cortical activity is difficult to determine because of concomitant physiological responses such as elevated body temperature and increased blood flow, which may influence oscillatory activity [84,85]. Conversely, the effects of moderate-intensity exercise are less likely influenced by such factors because the increase in body temperature is not as pronounced [96]. The results of studies on moderate-intensity exercise have mainly revealed an increase in alpha and beta activity in different regions of the brain, which can be explained by the fact that alpha activity is linked to arousal [97] and beta activity plays a role in maintaining exercise at a steady state [98]. Analysis of the effects of low-intensity exercise on cortical activity has not revealed any significant trends, the most frequent observation being the absence of significant changes in the oscillatory bands, exception of the alpha band. The effects on alpha band activity vary, with some studies reporting an increase [32,99,100], others a decrease [101–103], and still others showing no change [104]. Like studies on moderate-intensity exercise, research on low-intensity exercise has focused mainly on the activity of the alpha band, limiting discussion of the other oscillatory bands.

- Application of the EEG/$\dot{V}O_2$ ratio approach in exercise physiology and medicine.

The application of the EEG/$\dot{V}O_2$ ratio approach in exercise physiology and medicine offers a novel method for understanding the complex relationship between neural activity and metabolic demand during physical exertion. This innovative approach integrates EEG to monitor brain activity and oxygen consumption measurements to assess metabolic function, providing a comprehensive picture of how the brain and body respond to exercise. By analyzing the EEG/$\dot{V}O_2$ ratio, researchers and clinicians can better understand the cognitive and neural mechanisms underlying physical performance, fatigue, and recovery. This method has significant implications for optimizing athletic training, as it makes it possible to identify the mental states that correlate with peak performance and periods of reduced efficiency. For example, understanding how brain activity changes at different $\dot{V}O_2$max levels can help to design more effective training regimes that improve both physical and cognitive endurance. Furthermore, in the medical field, the EEG/$\dot{V}O_2$ ratio

can be used to adapt rehabilitation programs for patients suffering from cardiovascular or neurological disorders, ensuring that both the cognitive and physical aspects of recovery are taken into account. This dual approach can improve patient outcomes by enhancing not only physical capacity, but also mental resilience and cognitive function. This approach also makes it possible to study the effects of environmental stress factors, such as high altitude, extreme temperatures, or hypoxic conditions, on brain function and overall performance. By monitoring how the brain adapts to these challenging conditions, it is possible to develop strategies to mitigate their adverse effects, thereby improving safety and performance in extreme environments. In this way, the EEG/$\dot{V}O_2$ ratio represents a powerful tool for advancing our understanding of the dynamic interaction between the brain and body in both health and disease, paving the way for more integrated and effective approaches in exercise science and clinical practice.

5. Conclusions

In this study, we mainly demonstrated that, regardless of the occurrence of $\dot{V}O_2$pl, a decline was observed for all bandwidths according to the EEG/$\dot{V}O_2$ decline throughout the test. Therefore, we suggest the existence of a "EEG reserve depletion" while alpha activity in motor cortex is preferentially maintained. The EEG responses to fatigue in this study can be associated with other variables to determine brain behavior during exercise, both before and at the end of exercise. Information on heart rate, ventilatory thresholds and maximum oxygen consumption associated with EEG data could emerge from this integrated data analysis. We hypothesized that overall EEG activity would change as fatigue developed throughout both exercise durations and might depend on the sport experience profile. In addition, we hypothesized that EEG analysis could provide a predictive index of exercise exhaustion.

Research into changes in cortical brain activity during an incremental exercise test has produced mixed results. For example, Bailey and colleagues reported increases in alpha and beta frequencies throughout an incremental exercise test [31], whereas Robertson and Marino [33] observed increases in these frequency bands only until RCP, after which EEG activity decrease until the end of exercise.

Therefore, in order to go further on the debate on the impact of exercise intensification on the EEG response, we proposed here to have a systemic approach to exercise limitation, especially applied to the concept of $\dot{V}O_2$max, by merging the fields of neuroscience, biomechanics, and physiology. This could open up the black box of the "central governor" that has been at the heart of the debates on factors limiting $\dot{V}O_2$max.

In conclusion, the combination of all the scientific fields in this study could help delineate the signature of exhaustive exercise. We might then be able to identify the evolution of multiple signals during exercise and potentially anticipate the decision to stop this exercise by looking for a minimum EEG/$\dot{V}O_2$ threshold or a threshold for continuing exercise beyond a specific EEG/$\dot{V}O_2$ threshold.

6. Limitations

This study was conducted using an "open-loop" control mode, since the power was imposed by the experimenters. Consequently, the movements were pre-programmed or predetermined without continuous feedback from the sensory inputs. In real performance conditions, such as running, the subject is in a closed-loop condition and the EEG response could also be used as a pace controller [48]. This closed-loop configuration is probably the most appropriate exercise model for understanding individual critical threshold [105] and subjective experiences of fatigue, such as in a marathon race [106], and for understanding the limits of exercise tolerance with an integrative model [107,108]. However, our experimental study is limited by the small sample size, which restricts the statistical power and may affect the reliability and generalizability of the results. A smaller sample size increases the risk of type II errors, where true effects may not be detected, and reduces confidence in effect sizes estimates. This limitation may also lead to greater variability and margin of

error in the results, which could impact the robustness and reproducibility of our findings. Therefore, although our results provide valuable preliminary information, further research with larger and more diverse samples is essential to validate and extend these findings.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

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