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Validity of dynamical analysis to characterize heart rate and oxygen consumption during effort tests

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ABSTRACT

Performance is usually assessed by simple indices stemming from cardiac and respiratory data measured during graded exercise test. The goal of this study is to characterize the indices produced by a dynamical analysis of HR and VO₂ for different effort test protocols, and to estimate the construct validity of these new dynamical indices by testing their links with their standard counterparts. Therefore, two groups of 32 and 14 athletes from two different cohorts performed two different graded exercise testing before and after a period of training or deconditioning. Heart rate (HR) and oxygen consumption (VO₂) were measured. The new dynamical indices were the value without effort, the characteristic time and the amplitude (gain) of the HR and VO₂ response to the effort. The gain of HR was moderately to strongly associated with other performance indices, while the gain for VO₂ increased with training and decreased with deconditioning with an effect size slightly higher than VO₂ max. Dynamical analysis performed on the first 2/3 of the effort tests showed

similar patterns than the analysis of the entire effort tests, which could be useful to assess individuals who cannot perform full effort tests. In conclusion, the dynamical analysis of HR and VO₂ obtained during effort test, especially through the estimation of the gain, provides a good characterization of physical performance, robust to less stringent effort test conditions.

1 INTRODUCTION

2 Characterization of Heart Rate (HR) and oxygen consumption (VO₂) related to
3 mechanical power (i.e., speed or power) during standardized graded exercise test (GET) is an
4 unavoidable step in current athlete's performances assessment ¹. These two measurements are
5 also classically used in the scientific field of sport studies as one of the main physiological
6 output to characterize evolution of athlete's performance over time ²⁻⁴.

7 Current analysis of these parameters is based on two radically different approaches. The first
8 is the use of standard techniques, easily applicable and extensively used. The most common
9 index to characterize the HR recovery is the Heart Resting Rate (HRR) ⁵, commonly defined
10 as the difference between HR at the onset of recovery and HR one minute after. This
11 characterization is known to be a good predictor of cardiac problems in medicine ⁵, and is an
12 interesting indicator of physical condition and training ⁶. The maximum rate of HR increase
13 (rHRI) is a recent indicator showing correlation with fatigue and training in various studies ⁶.

14 This first type of approaches to characterize HR dynamics suffer from two important
15 drawbacks. First, these measurements mix the amplitude of the HR response to effort with its
16 temporal shape. For instance, someone reaching a maximum heart rate of 190 beat/minute
17 and decreasing to 100 beat/min in one minute will have the same HRR as another person
18 reaching 150 beats/minute and decreasing to 60 beats/minute in one minute, although the HR
19 dynamic is different. Secondly and more importantly, they use only a small fraction of the

20 information contained in the entire effort test (e.g., for HRR, the heart rate at the end of
21 exercise and the heart rate one minute later, so two minutes out of a test of 20 to 30 minutes).

22 Regarding standard analysis of respiratory parameters, the main indicators of athlete's
23 performing capacities are the maximal VO_2 reached during the exercise, the maximal aerobic
24 power or the maximal speed reached, and the values of power or speed at the two Ventilatory
25 Thresholds (VTs), corresponding to the lactic apparition (VT1) and the accumulation (VT2)
26 threshold ⁷. Although these VO_2 parameters are currently considered among the best indexes
27 of aerobic fitness evaluation ⁸, several drawbacks exist. First, determining them requires most
28 of the time a visual analysis of the data. Second, they make use of only a part of the gas
29 consumption dynamics, discarding the majority of the information contained in the entire
30 effort test.

31 The second approach, based on dynamical system modeling, could allow to more
32 accurately characterize the HR or VO_2 response during effort. Dynamical analysis based on
33 differential equations is an active subject of research in the behavioral field since the seminal
34 work of Boker ⁹ and has led to numerous studies in the field of psychology and to several
35 methodological advances ¹⁰. First order differential equation approach has the potential
36 ability to adjust HR measurement ^{11,12} and VO_2 dynamics during variable effort loads ¹³. We
37 propose here to use a simple first order differential equation coupled with a mixed effect
38 regression to quantify the link between the exercise load during effort test and the resulting
39 HR or VO_2 dynamics. Because dynamical models use all the information measured during
40 the effort test, it may allow to accurately assess performance indices using non-maximal
41 effort tests.

42 The aim of this study is to characterize the indices produced by the dynamical analysis
43 of HR and VO_2 for different effort test protocols. The construct validity of these new

44 dynamical indices will be provided by testing their links with their standard counterpart.
 45 Their ability to detect performance change over two different context of training load will
 46 determine their predictive validity and sensitivity to change. We will therefore analyze
 47 longitudinal data measured for two groups of young athletes with two different protocols.
 48 One group should show a performance increase following a three months training period, and
 49 the second group should have a performance decrease after an off-season of 6 weeks. The
 50 possibility to apply the proposed dynamical analysis to submaximal effort tests will be
 51 studied by comparing the result of the analysis performed on the full tests with the one
 52 performed on only the first part of the test.

53 **METHODS**

54 *Subjects*

55 To test the reliability of the dynamical analysis model, data were acquired in two
 56 different populations (Guadeloupe and Spanish athletes) subjected to two different profiles of
 57 exercise (step-by-step cycling and continuous intensity running increase) and physiological
 58 conditions (training and deconditioning), presented in Table 1.

Table 1 Biometrical data of the two groups studied in this study at baseline.

	Group 1	Group 2	p
Number of subjects	32	14	
Age (years)	15.06 (1.48)	15.36 (0.84)	0.487
Weight (kg)	62.54 (11.98)	64.41 (7.29)	0.593
Height (cm)	172.40 (8.84)	170.91 (4.34)	0.556
Gender (Male)	19 (59.4%)	14 (100.0%)	0.014

59
 60 Group 1 consists of 32 young athletes (19 males and 13 females; 15.1±1.5 year-old) of
 61 the Regional Physical and Sports Education Centre (CREPS) of French West Indies
 62 (Guadeloupe, France), belonging to a national division of fencing, or a regional division of

63 sprint kayak and triathlon. GET was performed at the end of the off-competition season, and
64 after 3 months of intense training (3-7 sessions/week). All athletes completed a medical
65 screening questionnaire, and a written informed consent from the participants and the legal
66 guardians was obtained prior to the study. The study was approved by the CREPS Committee
67 of Guadeloupe (Ministry of Youth and Sports) and the CREPS Ethics Committee and
68 performed according to the Declaration of Helsinki.

69 Group 2 consists of 14 young males, (15.4 ± 0.8 year-old) amateur soccer players from
70 Malaga (Spain), performing three weekly training sessions and one weekly competition. A
71 first GET was performed at the end of the soccer season and a second 6 weeks after. All
72 participants were warned to avoid any training activity during this time. The measurements
73 have been used in a previous publication ¹⁴ and was approved by the Research Ethics
74 Committee of the University of Málaga, Spain (EMEFYDE UMA: 2012-015 report) and
75 carried out according to the principles of the Declaration of Helsinki. Participation in the
76 study was voluntary, and prior to its initiation, written informed consent was obtained from
77 the participants and the legal guardians of those under 18 years of age.

78 *Effort test measurement*

79 Group 1 performed an incremental testing on an SRM Indoor Trainer electronic
80 cycloergometer (Schoberer Rad Meßtechnik, Jülich, Germany) associated to a Metalyzer 3B
81 gas analyzer system (CORTEX Biophysik GmbH, Leipzig, Germany). The SRM
82 cycloergometer is directly supervised by computer to automatically maintain a constant
83 mechanic workload by adjustment of the brake in accordance to the number of revolutions
84 per minute. Cardiorespiratory parameters were recorded cycle-to-cycle during all the test to
85 obtain HR and VO_2 all along the test session. The effort protocol used consisted of a 3 minute
86 rest phase, followed by a 3 min cycling period at 50 watts, followed by an incremental power
87 testing of +15 Watts by minute until exhaustion. Measurements of VO_2 , HR and mechanical

88 power during the last increment sustained by athletes were respectively considered as VO_2
89 max, HR max and Maximal Aerobic Power (MAP). At the end of the test, measurements
90 were prolonged during a 3 min period to record the physiological recovery of athletes.

91 Group 2 performed GET on a PowerJog J series treadmill connected to a CPX
92 MedGraphics gas analyzer system (Medical Graphics, St Paul, MN, USA) with cycle-to-
93 cycle measurements of respiratory parameters -including VO_2 , and HR- with a 12 lead ECG
94 (Mortara). The stress test consisted of an 8-10 min warm up period of 5 km.h^{-1} followed by
95 continuous 1 km.h^{-1} by minute speed increase until the maximum effort was reached. Power
96 developed during the effort test was calculated using the formula described by the American
97 College of Sport Medicine (ACSM). The latter determines an approximate VO_2 of runners¹⁵
98 associated to the Hawley and Noakes equation that links oxygen consumption to mechanical
99 power¹⁶.

100 *Truncated effort tests*

101 In order to test the robustness of the dynamical analysis, truncated effort tests were
102 generated from the maximal effort test for both groups. It consisted in removing the
103 measurements of the test for power (or speed) above $2/3$ of the maximum power (or
104 maximum speed) value, so that the maximum power (or speed) achieved during the truncated
105 test lies between the two ventilatory thresholds The recovery period was set as the recovery
106 measurements of the full effort test with values below the maximum value reached during the
107 truncated exercise. An example of truncated effort is presented in Fig1, for a VO_2
108 measurement during an effort test of group 1.

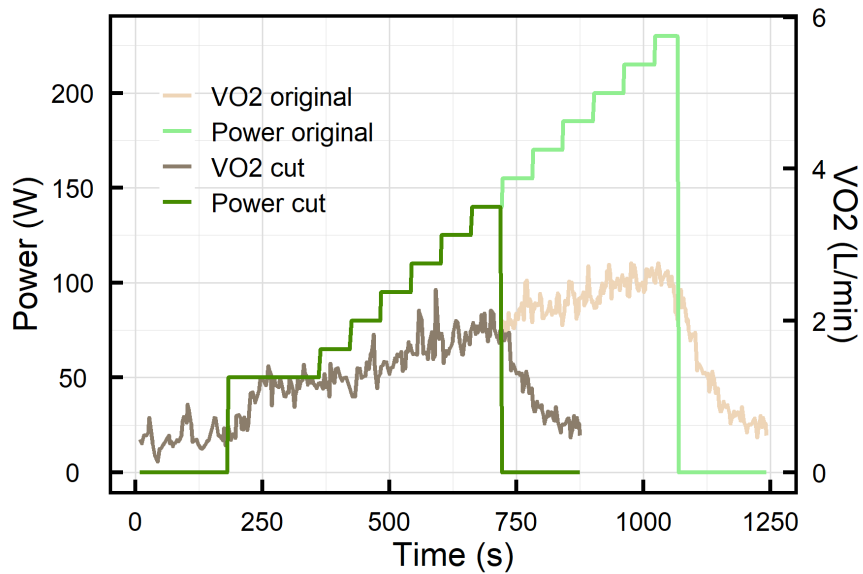


Fig1: VO_2 measured during a maximal effort test (light colors lines), and the truncated test generated from these data (dark colors lines)

109 *Standard indices:*

110 The HRR calculated is the standard HRR60, which is the difference between the HR
 111 at the onset of the recovery and the HR 60 seconds later. The ventilatory thresholds 1 (VT1)
 112 and 2 (VT2) are calculated using the Wasserman method using the minute ventilation
 113 VE/VO_2 for determining VT1 and VE/VCO_2 for VT2¹⁷. The rHRI is derived by performing a
 114 sigmoidal regression of HR before and during the first 3 min effort step (only in group 1) and
 115 calculating the maximum derivative from the estimated parameters, as described in¹⁸.
 116 Maximum aerobic power is the maximum power spend during the maximal effort test.
 117 HRmax and VO_2 max are the maximum values of the rolling mean of HR and VO_2 over 5
 118 points.

119 *New indices using dynamical analysis:*

120 A first order differential equation describes a relation between a time dependent
 121 variable, its change in time and a possible time dependent excitation mechanism. For a
 122 variable Y (HR or VO_2), it reads:

$$\dot{Y}(t) + \frac{Y(t) - Y_0}{\tau} = \frac{K}{\tau} \times P(t) \quad (1)$$

123 Where $\dot{Y}(t)$ is the time derivative of Y (i.e. its instantaneous change over time), Y_0 its
 124 equilibrium value (i.e. its value in the absence of any exterior perturbation) and $P(t)$ the
 125 excitation variable, that is the time dependent variable accounting for the exogenous input
 126 setting the system out of equilibrium. Equation 1 describes the dynamics of a self-regulated
 127 system that has a typical exponential response of characteristic time τ and an equilibrium
 128 value Y_0 in the absence of excitation (i.e. when $P(t) = 0$). For a constant excitation (i.e. a
 129 constant $P(t) = P$), the system stabilizes at a value KP after several τ . This value depends on
 130 both the system and the excitation amplitude (see Fig2 left panel).

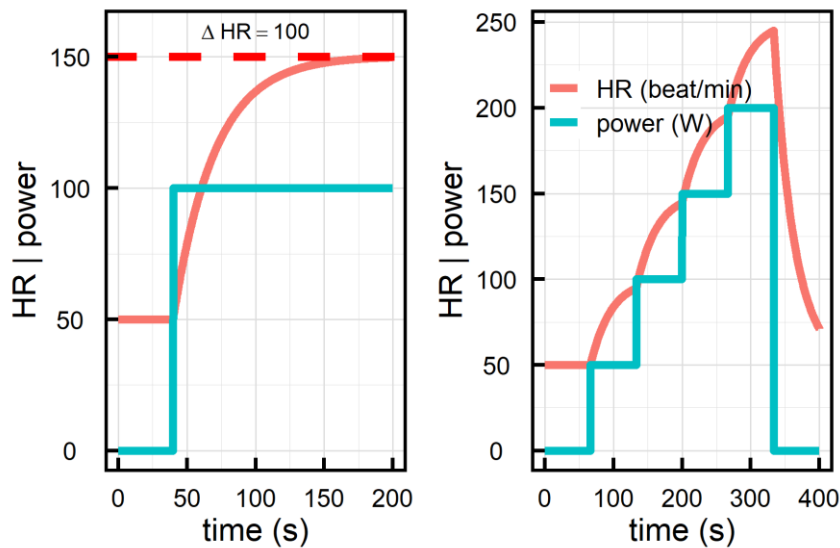


Fig2 simulated HR dynamics following equation 1, for two different efforts (left panel: constant effort, right panel: effort test of three incremental steps), an equilibrium value of 50 beats.min⁻¹, a decay time of 30 s and a gain of 1.

131 HR and VO₂ are two self-regulated features of our body: they respond to an effort
 132 with a certain characteristic time to reach a value corresponding to the energy demand¹⁹.
 133 Equation 1, as already demonstrated in¹³ for VO₂, can reproduce the dynamics of these two
 134 measures when considering that $P(t)$ is the power developed by the body during effort.

135 Assuming that HR or VO_2 follow equation 1, only three time-independent parameters are
136 needed to characterize and to predict their dynamics for any time dependent effort:

- 137 - Y_0 (i.e. HR_0 or VO_{20}) is the *equilibrium value*, i.e. the value in the absence of
138 effort.
- 139 - τ is the characteristic time or *decay time* of the evolution of the variable. It
140 corresponds to the time needed to reach 63% of the absolute change of value for a
141 constant excitation. For instance, for an individual running at 10 km/h and who
142 would have a total increase of HR of 60 beats/min for that effort, the decay time
143 would be the time needed to increase his heartbeat by 38 beats/min (60 beats/min
144 \times 63%).
- 145 - K , the *gain*, is the proportionality coefficient between a given effort increase and
146 the corresponding total HR or VO_2 increase (ΔHR and ΔVO_2). An illustration is
147 provided in Fig2 left panel: a HR gain of $K_{HR} = 1$ beat/min/W leads to a HR
148 increase of 100 beats/minute for a 100W effort increase, and to $\Delta HR = 200$
149 beats/min for a 200W effort increase.

150 An example of the dynamics for HR following equation 1 is given in Fig2 considering
151 $HR_0 = 50$ beats.min⁻¹, $\tau_{HR} = 30$ s, $K_{HR} = 1$ and two efforts types. These three coefficients
152 tightly characterize the dynamics of HR and allow us to generate the response to any effort.

153 The estimation of the three parameters characterizing the dynamics according to equation 1 is
154 done in a two-step procedure, consisting in first estimating the first derivative of the variable
155 studied over a given number of points with Functional Data Analysis (FDA) regression spline
156 method^{10,20}. It consists on generating a B-spline function that fits the outcome to be studied
157 and then estimating the derivative of that function. In order for the generated B-spline
158 function to be differentiable, it needs to be smooth. This is achieved through a penalty

159 function controlled by a smoothing parameter. This parameter was chosen to maximize the
160 R^2 , which is the goodness of fit of the model to the data.

161 Once the derivative estimated, a multilevel regression is performed to estimate the linear
162 relation between the derivative, the variable and the excitation (summarized by the three
163 parameters presented before).

164 This two-step estimation procedure has been extensively tested and described in a recent
165 simulation study ¹². It can be applied to data with non-constant time sampling if it contains
166 more than 5 points per typical decay time (in our case, at least one point every 20 seconds)
167 and has a measurement noise below 50% of the signal amplitude.

168 Once the three dynamical parameters estimated, an estimated curve can be reconstructed
169 performing a numerical integration of equation 1 (using the deSolve Package in R ²¹).

170 The above analysis procedure (estimation and estimated curve reconstruction) has been
171 embedded and described in the open-source library *doremi* ²² available in the open source
172 software R. Example code reproducing the analysis presented in this article can be found in
173 the example vignettes associated.

174 *Statistical analysis*

175 HR measurements with a rate of change higher than 20 beat.min⁻¹ from one
176 measurement to the next one were first removed as spurious results from the sensors.
177 Indices difference within each group between the first and the second measurement was
178 assessed using paired t test, and effect sizes were estimated by Cohen's d index. Associations
179 between standard physical performance indices and the results of our dynamical analysis
180 were assessed using Spearman rank correlation coefficients for continuous variables and
181 logistic regression for dichotomous variables. Training was operationalized as a binary
182 variable set to 0 for measurements before training for group 1 and after deconditioning for

183 group 2 (untrained situation), and to 1 for measurements after training for group 1 and before
184 deconditioning for group 2 (trained situation).

185 All analyses were performed using R version 3.4.2²³, the package *doremi*^{12,22} for the
186 dynamical analysis and the packages *data.table*, *Hmisc* and *ggplot2* for the data management
187 and statistical indicators.

188 RESULTS

189 The associations between standard indices were high, especially between the
190 maximum value of oxygen consumption (VO₂ max), the MAP achieved and the ventilatory
191 threshold powers for VO₂ (correlations ranging from 0.73 to 0.93). There was also a
192 significant negative correlation between rHRI and VO₂ max (correlation coefficient of -0.42,
193 p = 0.023), meaning that a higher maximum aerobic power reached during effort or a higher
194 maximal VO₂ is associated with a lower rate of HR increase during the first effort test (For
195 full details of these associations, for the first time of measurement, see Supplementary Table
196 1 online).

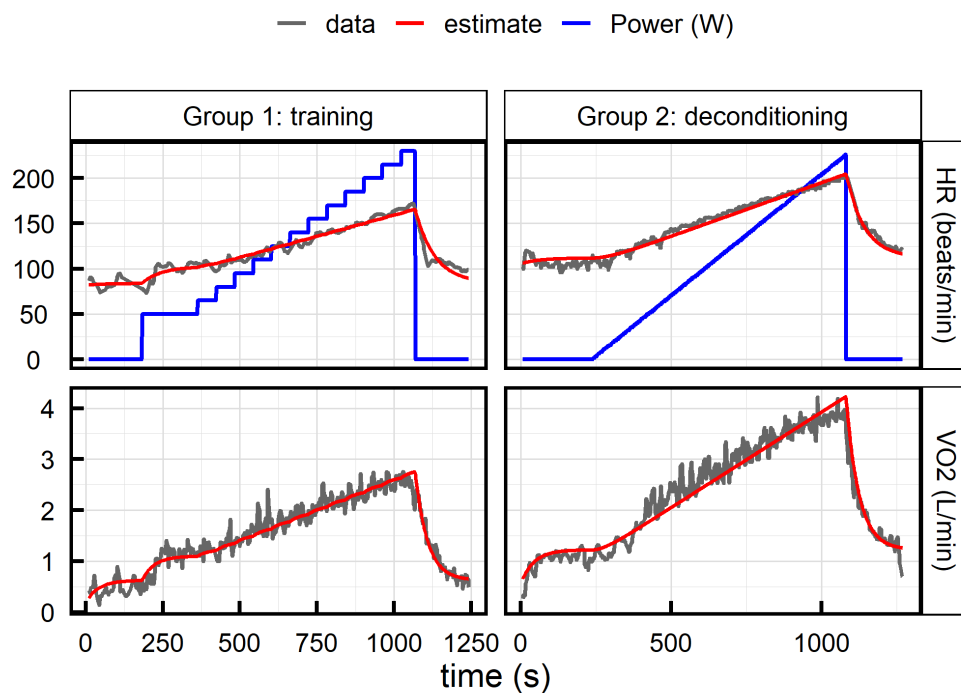


Fig3 Example of HR and VO₂ dynamics from one subject for each group. Blue line shows the power supplied by the subject during the effort, gray lines are the experimental measurement of HR or VO₂, and red lines shows the estimation given by the dynamical model.

197

198 Example of HR and VO₂ dynamics is given in Fig3, together with the estimated curve
199 obtained from the first order differential equation analysis. The model was very close to the
200 observed values for both HR and VO₂, and for both effort test protocols, with R² (median
201 [IQR]) of 0.96 [0.93, 0.97] for HR, 0.94 [0.92, 0.96] for VO₂ in group 1, and 0.95 [0.91, 0.97]
202 for HR, 0.94 [0.90, 0.96] for VO₂ in group 2. The estimated curve deviate from the
203 experimental data mainly at high effort intensity and at rest before the effort. The ensemble of
204 the estimated values compared to the true observed ones are presented in Supplementary Fig1
205 (online).

206 The dynamical analysis estimation of resting values overestimated the measured
207 values (HR measures averaged approximately 20 seconds before the first effort increase, see
208 Supplementary Table 2 online), partly because the participants did not provide enough values
209 before the start of the test. Thus, we will discard this index for the rest of the study.

210 VO₂ max and K_{VO_2} , the gain of VO₂ (i.e. proportionality coefficient between an effort
211 increase and the final VO₂ increase caused by this supplementary energy expenditure),
212 increased significantly during the 3 months training period of group 1, and decreased
213 significantly during the 6 weeks of deconditioning of group 2 (Table 2). The effect size was
214 slightly higher for K_{VO_2} than VO₂ max in the two groups and was higher for deconditioning
215 than for training for both variables.

216 A small decrease of the power of the first ventilatory threshold (power VT1) is also
217 observed in population 2. τ_{VO_2} , the response time τ of VO₂ to the effort is shorter than τ_{HR} ,

218 the response time of HR, in both populations. The HR gain (K_{HR}) is remarkably similar in
 219 both groups, and unaffected by training or detraining. The relative standard deviation of τ_{VO_2}
 220 (between 35% and 50%) is higher than the relative standard deviation of the associated gain
 221 (K_{VO_2}). None of the dynamical parameter (gain K or decay time τ) displayed significant
 222 correlation with the length of the experimental data record.

Table 2 Comparison of the classical indices and the indices stemming from the dynamical analysis of VO_2 and HR: the gain K and the decay time τ .

Indices	Measurement 1	Measurement 2	p value	Cohen's d
Group 1 : training				
MAP (W)	239.8 (55.2)	242.7 (60.0)	0.85	
VO ₂ max (mL/min/kg)	33.6 (6.1)	42.5 (7.4)	<0.01	1.31
HR max (beat/min)	186.9 (10.1)	188.5 (7.2)	0.51	
Power VT1 (W)	97.2 (50.7)	113.9 (40.9)	0.16	
Power VT2 (W)	174.7 (54.5)	181.0 (49.8)	0.64	
HRR (beat/min)	35.0 (12.3)	36.9 (9.6)	0.53	
rHRI (beat/min/s)	0.5 (0.2)	0.5 (0.1)	0.84	

τ_{HR} (s)	106.4 (33.7)	108.3 (32.2)	0.82	
K_{HR} (beat/min/W)	0.43 (0.13)	0.43 (0.12)	0.96	
τ_{VO_2} (s)	58.9 (19.9)	57.5 (27.7)	0.84	
K_{VO_2} (mL/min/W)	6.9 (1.7)	9.2 (1.1)	<0.01	1.61
Group 2 : deconditioning				
MAP (W)	231.9 (31.1)	226.4 (27.4)	0.62	
VO ₂ max (mL/min/kg)	62.5 (5.6)	49.9 (6.4)	<0.01	2.11
HR max (beat/min)	199.6 (7.2)	200.6 (5.0)	0.65	
Power VT1 (W)	116.3 (20.8)	101.1 (16.9)	0.04	0.80
Power VT2 (W)	184.0 (26.6)	165.2 (29.0)	0.10	
HRR (beat/min)	38.3 (9.0)	41.3 (10.3)	0.50	

τ_{HR} (s)	100.2 (37.3)	91.7 (25.1)	0.50	
K_{HR} (beat/min/ W)	0.4 (0.1)	0.4 (0.1)	0.64	
τ_{VO_2} (s)	54.6 (19.4)	58.4 (30.9)	0.70	
K_{VO_2} (mL/min/W)	12.6 (1.7)	8.9 (1.1)	<0.01	2.57

Effort test measurements have been performed before and after the 3-month training in group 1 and before and after the 6-week deconditioning in group 2. VO₂: O₂ consumption; HR: Heart Rate; MAP: Maximal Aerobic Power; HRR: Heart Resting Rate; rHRI: rate of Heart Rate Increase; VT: Ventilatory Threshold. Group 2 does not have rHRI because of the

protocol used: the linear increase of power does not allow proper calculation of rHRI. Effect size is given by the Cohen's d of the t test.

223 In univariable analysis, τ_{HR} was correlated with measures of HRmax and HRR (Table
224 3), and K_{HR} (i.e., proportionality coefficient between effort increase and final HR increase
225 caused by this supplementary energy expenditure) was negatively correlated with weight,
226 maximal aerobic power, maximum O₂ consumption, and the two ventilatory thresholds. Only
227 in group 1, K_{HR} was also negatively correlated with age, height and rHRI, whereas a
228 correlation with HRmax is found only in group 2. In other words, a decrease of K_{HR} , (i.e. a
229 decrease of ΔHR for a given effort) was linked with an improvement of oxygen maximal
230 consumption, maximal aerobic power and the power corresponding at the two transition
231 thresholds. Overall, correlations with new indices were higher than the correlations found
232 between standard HR indices and other performance variables (see Supplementary Table 1
233 online). In a multivariable analysis performed in each group including age, weight, height,
234 VO₂ max and power at ventilatory thresholds, only weight remained significantly associated
235 with K_{HR} (see Supplementary Table 3 online).

236

Table 3 Spearman correlation coefficients between the gain K and the decay time τ of HR and VO_2 for both populations, physiological characteristics and standard analysis indices.

Group 1 : training				
	τ_{HR}	K_{HR}	τ_{VO_2}	K_{VO_2}
Age	0.11	-0.43**	-0.01	0.06
Weight	0.07	-0.73***	-0.06	0.13
Height	-0.06	-0.55***	-0.09	0.05
MAP	0.09	-0.79***	0.12	0.01
VO ₂ max	0.07	-0.65***	-0.10	0.57***
Power VT1	0.13	-0.44***	0.03	0.09
Power VT2	0.10	-0.63***	-0.03	0.12
HR max	0.32*	0.16	0.02	0.18
HRR	-0.52***	-0.14	0.06	0.06
rHRI	-0.01	0.37**	0.19	-0.24
Group 2 : deconditioning				
Age	0.07	-0.08	0.10	0.20
Weight	-0.11	-0.63***	-0.34	0.08
Height	0.16	0.05	-0.16	-0.13
MAP	0.28	-0.73***	-0.25	-0.04
VO ₂ max	-0.05	-0.49**	-0.25	0.67***
Power VT1	-0.05	-0.54**	-0.15	0.19
Power VT2	0.01	-0.49*	0.10	0.33
HR max	0.38*	0.49**	0.40*	-0.10
HRR	-0.72***	0.16	-0.32	-0.08

MAP: Maximal Aerobic Power; HR: Heart Rate; HRR: Heart Resting Rate; VT: Ventilatory Threshold; rHRI: rate of Heart Rate Increase. Significance is indicated as follows: *: $p < 0.05$; **: $p < 0.01$, ***: $p < 0.001$

238 VO₂ decay time (τ_{VO_2}) was globally independent of physiological variables and
 239 standard indices (Table 3), whereas K_{VO_2} was strongly associated with VO₂max. In a
 240 multivariable analysis performed on each group including age, weight, height, training,
 241 VO₂max and power at ventilatory thresholds, VO₂max and training remained significantly
 242 associated with K_{VO_2} (see Supplementary Table 3 online). In group 1, training increased the
 243 K_{VO_2} of 1.1 mL/min/W on average and an increment of 1L/min of VO₂ max increased K_{VO_2}

244 by 2.7 mL/min/W on average. In group 2, the deconditioning decreased K_{VO_2} by 2.1 and the
 245 decrease of 1L of VO_2 max lowered the VO_2 gain by 1.8 mL/min/W.

246 *Truncated effort test*

247 When performing the dynamical analysis on the truncated effort tests (see Fig1), the
 248 calculated R^2 were slightly lower than the analysis performed on the entire test (0.90 [0.88,
 249 0.94] for VO_2 and 0.93 [0.89, 0.95] for HR in group 1, and 0.90 [0.87, 0.93] for VO_2 and 0.90
 250 [0.87, 0.95] for HR in group 2. The resulting dynamical indices were highly correlated with
 251 the one calculated on the entire effort test, as presented in Fig4.

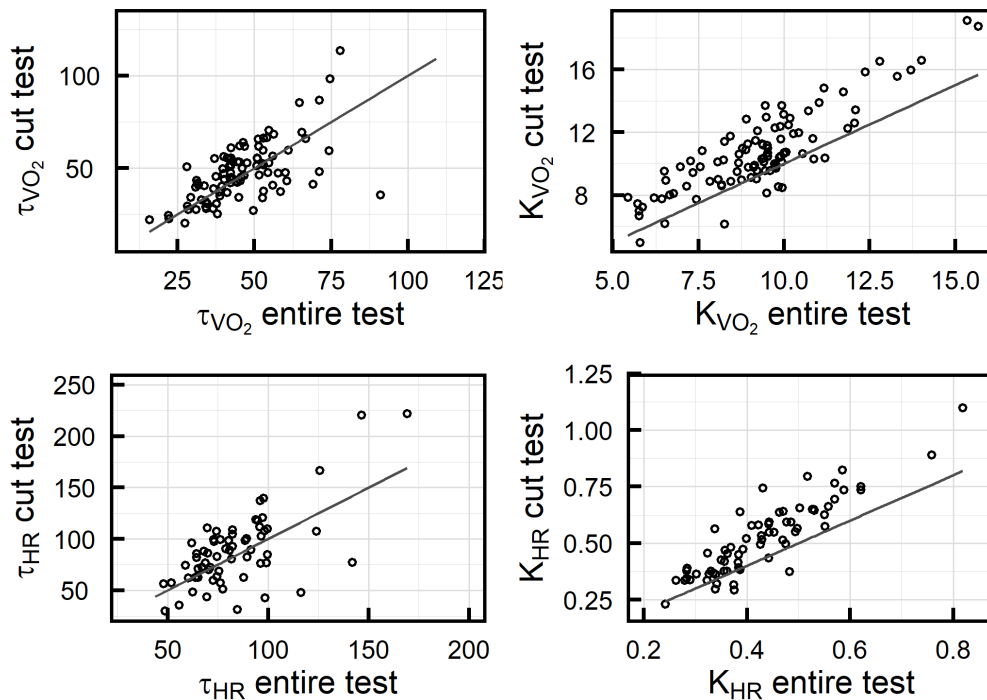


Fig4 comparison of the dynamical indices estimated on the entire effort test (x axis) and on the truncated effort test (y axis) for VO_2 (top row) and HR (bottom row). The solid black lines represent the identity.

252 The gain estimated on the truncated effort was slightly higher than the one estimated
 253 on the entire effort test. Correlation between the gain (for VO_2 and HR) and the other
 254 performance indices remained similar to the ones observed in Table 3. The VO_2 gain K_{VO_2}
 255 estimated on the truncated effort test still significantly changed between the two time points
 256 for both groups: from 8.9 (1.6) to 10.2 (1.8) mL/min/W for group 1 ($p < 0.01$, Cohen's $d =$

257 0.754), and from 15.0 (2.3) to 12.2 (1.7) ML/min/W for group 2 ($p < 0.01$, Cohen's $d = 1.38$).
258 In summary, the VO_2 gain presented higher values but still significantly increased with
259 training and decreased with deconditioning.

260

261 **DISCUSSION**

262 *Main findings*

263 Modeling the evolution of HR and VO_2 during effort tests with a first order
264 differential equation driven by the power spent during the effort produced an estimation able
265 to reproduce in average 95% of the observed variance of HR or VO_2 . The model was
266 successfully tested in two different populations (Guadeloupe and Spanish athletes) subjected
267 to two different profiles of exercise (step-by-step cycling and continuous intensity running
268 increase) and physiological conditions (training and deconditioning). The dynamical analysis
269 provided three indices: the equilibrium value or resting state, the decay time, and the gain or
270 proportionality between a given effort increase and the corresponding total increase in HR.
271 HR gain was correlated to the main indices of athlete's performance (MAP, VO_2 max, VT1
272 and VT2), which was not the case of other standard HR indices. Furthermore, VO_2 gain was
273 sensible to change in training or physical deconditioning. Finally, the indices obtained when
274 modeling truncated effort test (using about the first 2/3 of the effort tests data) had similar
275 characteristics, showing the robustness and usefulness of such approach to incomplete effort
276 tests. Such incomplete tests could occur due to lack of time but also when assessing older or
277 sick persons.

278 *Standard indices*

279 Using standard indices, it was possible to assess the relevance of the
280 training/deconditioning conditions used for this study. Results were in line with those

281 obtained by other studies ^{6,19}, thus confirming the quality of the effort tests results in the two
282 groups of athletes. In particular, the relationships between ventilatory thresholds (VT),
283 maximal aerobic power (MAP) and maximum oxygen consumption (VO₂ max), as well as
284 the change in VO₂ max after 3 months of training and after 6 weeks of deconditioning, were
285 in accordance with expected results ²⁴. VO₂ max variation was also more pronounced in the
286 deconditioning group than in the training one, as reported in previous observations ^{25,26}.
287 Concerning rHRI, the negative correlations with VO₂ max and MAP was reported previously
288 and is due to a parasympathetic withdrawal with sympathetic activation causing a relatively
289 slower HR increase in response to intensity increase for well-trained athletes when compared
290 to untrained ^{3,6}.

291 *Dynamical analysis*

292 There was a moderate correlation between VO₂ gain (K_{VO_2}) and VO₂ max ²⁷. Under an
293 assumption of linearity between mechanical workload and O₂ consumption, VO₂ max
294 corresponds to the oxygen consumption for the MAP expenditure and is directly linked to
295 K_{VO_2} :

$$VO_{2max} = VO_{2resting} + MAP \times K_{VO_2} \quad (2)$$

296 However, VO₂ max is estimated via a single experimental measurement,
297 supposed to be the VO₂ at the maximum effort achieved by the athletes. The ability to reach
298 maximum capacities during effort test is subject to several internal and external factors such
299 as athlete's engagement, mood state, fatigue and many others. Furthermore, the linear relation
300 between energy demand and O₂ consumption may not hold for high power expenditure ²⁸,
301 and thus VO₂ max may not be representative of physical performance for intermediate efforts.
302 In contrast, K_{VO_2} is estimated from the entire VO₂ dynamics during the effort test, yielding a
303 robust estimate of the VO₂ response to effort. As a consequence, the VO₂ gain estimated on

304 truncated effort tests was still sensible to training and deconditioning and seems a promising
305 performance index for submaximal effort test, such as those employed for patients suffering
306 chronic disease or for elderly patients.

307 The typical response time (i.e. the decay time τ) of VO_2 was shorter than the HR one,
308 in agreement with previous results²⁹. This temporal delay of HR compared to VO_2 kinetics is
309 due to the fact that heart flow regulation is partially driven by the oxygen demand of the
310 organism detected via chemoreceptors, causing the HR increase to be a consequence of the
311 VO_2 increase³⁰.

312 The high variability of the decay time estimated, may be explained by the different
313 energetic profiles of the athletes according to their sport discipline^{31,32} or soccer field
314 position³³ that could modify the kinetic of the VO_2 curve to reach the plateau at each
315 increment step of the protocol. The variability of the gain value is the result of the aerobic
316 metabolic efficacy, which is constant according to the substrate³⁴, and the cycling or running
317 efficacy, which is globally similar in a homogenous population of athletes. These differences
318 may participate to the higher variability of the decay time estimated, compared to the
319 variability of the gains.

320 The negative link between the K_{HR} and subject weight may be explained by the
321 known association between fat-free mass weight and heart's left ventricular size and mass³⁵.
322 This association, reflecting a well-trained heart in heavier athletes, results in a lower ΔHR for
323 a given effort and so a lower K_{HR} .

324 *Strength and weakness*

325 The main strength of this study is the use of two different populations of athletes, with
326 two different effort tests and two different training schemes, showing its potential
327 generalizability. Nevertheless, further study will need to extend these results to older adults,

328 young children, and people with strong sedentary habits. A second strength is related to the
329 analyses used, which allowed the estimation of performance indices without a maximum
330 effort test. These analyses pave the way to obtaining accurate performance indices and
331 information on training or deconditioning among larger groups of the population, such as the
332 elderly, or patients at risk of cardiovascular events. The availability of ready to use, open
333 source, tools for such analysis should facilitate its use for researchers and sport coaches ²².

334 As for limitations, the dynamic model used in this study made three assumptions that
335 led to slightly suboptimal fits. First, the assumption that the equilibrium value is constant
336 before and after the effort does not hold and led to the overestimation of these value. Indeed,
337 HR and VO₂ are known to decrease back to their resting value on a longer time scale due to
338 the reduction of blood volume (i.e. dehydration), the evacuation of the heat accumulated
339 during the muscular contractions, or the over-activation of the sympathetic system during
340 exercise ³⁶. The second assumption is that the entire dynamics has one unique characteristic
341 exponential time, making the model unable to account for cardiac drift associated to
342 prolonged effort or any long-term modification of the variable dynamics. The third
343 assumption is that the gain of VO₂ and HR is constant along the effort, i.e. that an increase of
344 exerted power leads to the same final increase of HR or VO₂. However, it is known that the
345 VO₂ dynamics saturates at high effort intensities³⁷ and that the HR response to effort
346 diminishes after the second ventilatory threshold (the inflexion point of the heart rate
347 performance curve³⁸). The simple model proposed in this article cannot account for such
348 dynamics change, and instead estimates an average gain over the entire effort test. This leads
349 to the increased difference between the estimated curve and the experimental data at high
350 effort intensity. It also explains the higher gains estimated for the truncated effort test, which
351 do not include the part of the effort where the real gain is actually diminishing.

352 Possibility to release the restrictions listed above is of high interest and is the subject
353 of current research. However, despite the fact that the model can still be improved, it already
354 provides indices with good sensibility to performance change and cardio-respiratory indices
355 used to measure fitness.

356 **CONCLUSION**

357 The dynamical analysis of heart rate (HR) and oxygen consumption (VO_2) during
358 effort appears to be relevant to evaluate performing capacities of athletes and its evolution. It
359 reproduced in average 95% of HR or VO_2 dynamics using only three estimated
360 cardiovascular indices. It was more sensitive to training and deconditioning than classic
361 indices. Furthermore, its ability to extrapolate VO_2 and HR indices from truncated effort tests
362 using only the first steps of the exercise could place it as a valuable tool for evaluate
363 functional capacity from participants unwilling or unable to do maximal exercise testing.

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