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A MULTIDISCIPLINARY APPROACH TO OVERREACHING DETECTION IN ENDURANCE TRAINED ATHLETES

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► **To cite this version:**

Yann Le Meur, Christophe Hausswirth, Françoise Natta, Frank Bignet, Pierre Vidal. A MULTIDISCIPLINARY APPROACH TO OVERREACHING DETECTION IN ENDURANCE TRAINED ATHLETES. *Journal of Applied Physiology*, 2012, 114 (3), pp.411-420. 10.1152/jappphysiol.01254.2012 . hal-01835107

HAL Id: hal-01835107

<https://insep.hal.science//hal-01835107>

Submitted on 11 Jul 2018

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1 **AUTHOR CONTRIBUTIONS**

2

3 The experiments were conducted 32 in the laboratory of the National Institute of Sport, Expertise and

4 Performance, Paris, France

5

6 *Conception and design of the experiments:*

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9

10 *Collection of the data*

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17 *Drafting the article or revising it for important intellectual content:*

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20

21 All authors approved the final version of the manuscript.

1 **ABSTRACT**

2

3 In sport, high training load required to reach peak performance push human adaptation to their limits.
4 In that process, athletes may experience general fatigue, impaired performance and may be identified
5 as overreached (OR). When this state lasts for several months, an overtraining syndrome is diagnosed
6 (OT). Until now, no variable *per se* can detect OR, a requirement to prevent the transition from OR to
7 OT. It encouraged us to further investigate OR using a multivariate approach including physiological,
8 biomechanical, cognitive and perceptive monitoring. Twenty-four highly trained triathletes were
9 separated into an overload group and a normo-trained group (NT) during three weeks of training.
10 Given the decrement of their running performance, eleven triathletes were diagnosed as OR after this
11 period. A discriminant analysis showed that the changes of eight parameters measured during a
12 maximal incremental test could explain 98.2% of the OR state (lactataemia, heart rate, biomechanical
13 parameters and effort perception). Variations in heart rate and lactataemia were the two most
14 discriminating factors. When the multifactorial analysis was restricted to these variables, the
15 classification score reached 89.5%. Catecholamines and creatine kinase concentrations at rest did not
16 change significantly in both groups. Running pattern was preserved and cognitive performance
17 decrement was observed only at exhaustion in OR subjects. This study showed that monitoring various
18 variables is required to prevent the transition between NT and OR. It emphasized that an OR index,
19 which combines heart rate and blood lactate concentration changes after a strenuous training period,
20 could be helpful to routinely detect OR.

1 INTRODUCTION

2

3

4 Increases in training and volume are typically undertaken by athletes in an attempt to enhance
5 physical performance. High training loads (i.e. increased training volume and intensity) can place
6 significant stress on the athlete's cognitive and physiological systems and if not matched by
7 appropriate rest/recovery can lead to maladaptation, leading to increased fatigue and reduced
8 performance (30, 41). When athletes require several days or weeks to recover physical performance,
9 they are diagnosed as being overreached (OR) (30). Common symptoms reported with OR include
10 general fatigue, sleep disorders, decreased appetite, loss of body weight, anxiety, reduce motivation,
11 lack of concentration and variation of mood (18). In severe cases of maladaptive training, known as
12 overtraining (OT), athletes may have reduced performance capacity either with or without these
13 clinical symptoms that remain for several months or years. This most severe form of training
14 maladaptation presents a serious threat for athletic performance and health. The currently accepted
15 method for diagnosing OR/OT is to monitor performance after completion of a resting period of
16 several days or weeks (18). Nevertheless, this method is frequently rejected by coaches and athletes
17 because it may endanger the training continuum and it could lead to potential detraining. It is therefore
18 important to identify early markers of OR/OT to limit the occurrence of these training maladaptation
19 forms in population at risk.

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Many physiological variables have been recorded to detect OR and OT. One of the most reported physiological measures in endurance athletes has been a right shift in the lactate curve (4, 16, 22, 28, 39, 44). However, it has not been reported by all investigators (10, 26). Similarly, decreased nocturnal urinary catecholamine excretion has been associated with OT in endurance athletes and interpreted as lowered intrinsic sympathetic activity (25, 29). Nevertheless, a reduced intrinsic sympathetic activity has not been observed in all studies investigating OR/OT (19, 44, 46). A decrease in the ratio between the hormones testosterone or free testosterone and cortisol has also been proposed as a physiological marker of "anabolic-catabolic balance", a putative tool in the diagnosis of OT (1). Again, not all studies have observed changes in these variables with OR/OT (25, 29, 43, 46), and therefore, they are not considered as a good independent measure of maladaptive training (18). Finally, changes in heart rate (HR) at rest, and during both submaximal and maximal exercise have been reported to be associated with OR in various sports (9, 10, 19, 22, 26, 39). However, a recent meta-analysis examining the effect of overload training on resting, submaximal and maximal exercise HR and heart rate variability demonstrated that the small to moderate changes in these variables limits their clinical usefulness as idiosyncratic markers of OR and OT (5). Altogether then, the lack of consensus amongst research suggests that independent physiological markers may have limited practical usefulness if used as early warning markers of OR/OT.

38 In that context, there has been increasing interest in the application of cognitive tests as early
39 warning measures of both OR and OT athletes (12, 13, 21, 31, 32). Nederhof et al. (32), reported that
40 executive functions can be influenced by training tolerance and suggested that alterations in these
41 functions may be an early indicator of maladaptive physical training. This hypothesis was
42 strengthened by three studies that reported small increases in response time and increased number of
43 mistakes in Stroop test at rest in OR and OT athletes (12, 13, 21). It remained that large inter-
44 individual variability in the results of the cognitive tests limited their usefulness to assess a state of
45 OR, especially when used alone. Also, cognitive performances had been assessed at rest and not
46 during exercise, which could be a more suited measure to detect maladaptation in athletes.

47

48 In summary, investigations into early warning markers of OR / OT was still elusive and
49 idiosyncratic physiological, biomechanical and cognitive variables that could identify OR remained to
50 be found (18, 35, 45). It led us to propose a multivariate approach to identify athletes at risk of
51 OR/OT. In order to test that hypothesis, we simultaneously monitored physiological, cognitive and
52 biomechanical parameters at rest and during exercise in athletes progressively driven to OR by a
53 prolonged period of overload training. We chose triathletes because they often undertake heavy loads
54 during training and therefore have been reported to be at risk of OR and OT.

55

56 **Methods**

57

58 *Ethical approval*

59

60 Twenty-four well-trained triathletes volunteered to participate in this study. All subjects had
61 competed in triathlons for at least 2 years and were training a minimum of 6 times per week. The
62 experimental design of the study was approved by the Ethical Committee of Saint-Germain-en-Laye
63 (acceptance no. 10054) and was done in accordance with the Declaration of Helsinki. Prior to
64 participation in the investigation, subjects underwent medical assessment. After comprehensive verbal
65 and written explanations of the study, all subjects gave their written informed consent.

66

67 The subjects were randomly assigned to either the experimental group (intensified training
68 (IT) group) or the control group (normal training group, NT) according to a matched group
69 experimental design based on maximal oxygen uptake ($\dot{V}O_{2max}$) and maximal aerobic speed (MAS).
70 Subjects' characteristics are presented in Table 1.

71

72 *Experimental protocol*

73

74 The protocol is illustrated in Figure 1. The investigation was conducted in September/October
75 at the end of the competitive triathlon season to ensure a high fitness level for all participants. The
76 training of each triathlete was monitored for a period of 7 weeks in total, which was divided into three
77 distinct phases. The two first phases were similar for both IT and NT groups. The first phase (I)
78 consisted of 3 weeks during which the subjects completed their usual amount and type of training
79 (classic training). The second phase (II) consisted of one week of moderate training during which the
80 subjects were asked to divide their normal training week by a half (recovery week). During the third
81 period (III), the IT group completed a 3-week intensified program designed to deliberately overreach
82 the triathletes; the duration of each training sessions of the classic training period was increased by
83 40%. The NT group reproduced its classic training program during the same period. Throughout the
84 entire experiment, the same sport scientist coached all triathletes. Training schedule was controlled to
85 remain similar during each week of phase III. To avoid injuries, particular attention was devoted to
86 daily feedback obtained from the triathletes. Throughout the entire study, heart rate was recorded
87 during training to ensure that the triathletes adhered to prescribed training. At the end of phases II and
88 III, the triathletes performed a maximal incremental running test on a 340-m indoor running track. To
89 ensure that performance variations during the maximal incremental runs were due to the global
90 training regimen and not to the training session(s) performed the day before each test, the subjects
91 were required to respect a 24 h rest period before each maximal incremental run session.

92

93 *Assessment of energy intake*

94

95 During the 48 h prior, each maximal oxygen uptake ($\dot{V}O_{2max}$) test, the triathletes were
96 required to follow a nutritional plan in order to ensure muscle glycogen store resynthesis. They were
97 allowed access to a buffet-type array of breakfast and meals foods and instructed to eat until satiety
98 was reached. Breakfast consisted of a variety of macronutrients from both solid and liquid energy
99 sources. The selected foods included an assortment of cereals, bread, fruit, yogurt, milk, juice, ham
100 and cheese. In the lunch and dinner meals, athletes ate a mixed salad as starter, then white meat during
101 lunch and fish during dinner. The side plate consisted of a mixed of 50% carbohydrates (i.e., pasta,
102 rice, noodles) and 50% of vegetables (i.e., green beans, broccoli, tomatoes). One fruit and one yogurt
103 were added as dessert, for lunch and dinner.

104

105

106 *Maximal running test*

107

108 The triathletes completed a maximal incremental running test on a 340-m indoor track to
109 determine their $\dot{V}O_{2max}$ and the velocity at which $\dot{V}O_{2max}$ occurred ($v\dot{V}O_{2max}$). The test began at 11

110 km·h⁻¹ and the speed was increased by 1 km·h⁻¹ every 3 minutes until volitional exhaustion. A rest
111 period of 1-min was provided between each running step. The triathletes followed a cyclist travelling
112 at the required velocity to ensure that the subjects were respecting the imposed pace. Visual marks
113 were set at 20 m intervals along the track. The cyclist received audio cues via an mp3 player; the cue
114 rhythm determined the speed needed to cover 20 m. The coefficient of variation of running speed
115 between the tests pre- and post-phase III for each running step was subsequently calculated in order to
116 assess the reproducibility of this parameter between the two tests.

117

118 *Physiological parameters*

119

120 Peripheral venous blood samples were taken from an antecubital vein of participants before
121 each running test. Samples were drawn into non-additive tubes under sterile conditions. Serum was
122 separated from whole blood by centrifugation at 1,000 g for 10 min at room temperature. An
123 OLYMPUS 2700 analyzer (Beckman Coulter, Brea, USA) was used for simultaneous assay with
124 reagents from the manufacturer of Creatine Kinase (CK). Plasma adrenalin and noradrenalin were
125 measured in high-performance liquid chromatography with electrical detection (Laboratoire Medibio,
126 Montargis, France).

127

128 *Metabolic parameters*

129

130 Between each increment, blood samples were taken from the participants' ear lobes during a
131 1-min rest period and analyzed using a Lactate Pro system (36). Oxygen uptake ($\dot{V}O_2$) and expiratory
132 flow (\dot{V}_E) were recorded breath-by-breath with a telemetric system collecting gas exchanges (Cosmed
133 K4b², Rome, Italy) (11), which was calibrated before each test. Heart rate values (HR) were monitored
134 every second using a Polar unit. Expired gases and HR values were subsequently averaged every 5 s
135 and were analysed (i.e., mean value) on time periods corresponding to the last 30s of each running
136 step. $\dot{V}O_{2max}$ was determined at exercise cessation when a plateau in $\dot{V}O_2$ despite an increase in
137 running speed was observed. If the subjects did not demonstrate any plateau in $\dot{V}O_2$, the test was
138 considered to be maximal, when the respiratory exchange ratio value exceeded 1.15 and maximal HR
139 value was over 90% of the predicted maximal value. The lactate threshold (LT) was assessed
140 according to the D-max method previously described by Cheng et al. (7).

141

142 *Biomechanical parameters*

143

144 *Kinetic measures.* An area of biomechanical data collection was installed in a particular
145 location of the indoor running track. This area was equipped with six adjacent force platforms
146 (Z2074AA, Kistler, Switzerland) embedded in the track and covered with a layer of tartan, so as to not
147 influence or disturb the triathletes while running. The total platform surface was approximately 6.6 m
148 long and 0.6 m wide and the output signals of the six platforms were acquired in series at 1000 Hz.
149 This length enabled data recording of at least four leg support phases (two left-side and two right-side
150 supports) regardless of the running speed. This device gathered, for each instant of the support phase,
151 the lateral (Fx), anteroposterior (Fy) and vertical (Fz) components of the force exerted by the
152 triathletes on the ground. The data collected were propulsion (PI_{mn}) and braking impulses (BI_{mn}),
153 peak vertical impact (Rz1_n), maximum peak vertical force (Rz2_n), support (dS), aerial (dA) and
154 braking durations (dB_n). Impulses and forces were normalized to body weight (x 1000 for impulses).
155 Braking duration was normalised to support duration.

156

157 *Kinematic measures.* The movement acquisition system was a Vicon optoelectronic device
158 (Oxford, United Kingdom), which uses 12 T10 cameras (resolution: 1megapixels) to follow and
159 record in 3D the position of set retroreflective (passive) spherical markers. The acquisition frequency
160 was set at 200 Hz. To reduce the effects of sliding of the markers, the triathletes were dressed in tight
161 fitting outfits and markers were fixed with double-sided tape and their contact was reinforced with
162 elastic adhesive strips.

163 Recordings from the force-platform and the video acquisition systems were synchronized.
164 Depending on the running speed, the triathletes ran between one and three times in this area. The data
165 collected were step length (L_{xn}) and width (L_{yn}), which were normalized to leg length and analyzed
166 using mean values for each running stage.

167

168 ***Cognitive performance.***

169

170 During the maximal incremental running test, subjects had to respond to audio stimuli
171 occurring in the second half of each 3-minute running stage.

172

173 *Double-task.* The system was comprised of two modified nunchuks (Nintendo Wii, Tokyo,
174 Japan), an mp3 player and recorder, earphones and linking audio cables. Nunchuks were chosen based
175 upon their light-weight and ergonomic design. To avoid any confusion, the upper analog stick was
176 removed, the middle finger button was locked in the pressed down position and only the forefinger
177 button was kept functional. Custom electronics allowed forefinger button actions to be recorded along
178 with the given audio stimuli. The whole system weighed approximately 70 g.

179 Audio stimuli were delivered through earphones and consisted of 30 single and double, high-
180 and low-pitched tones, randomly spaced in a 90s mp3 file. When hearing a single low-pitched or

181 double high-pitched tone, the triathlete was required to press down the left nunchuk button. Upon
182 hearing a single high-pitched or double low-pitched tone, the triathlete was required press the right
183 nunchuk button. All triathletes were instructed to respond as fast as possible. One week before the first
184 maximal incremental running test, they received an mp3 test file for training, and repeated this training
185 prior to each maximal incremental running test.

186 High- and low-pitched tones were respectively set as 5000 Hz and 150 Hz sine waves. Such
187 frequencies allowed the triathletes to unequivocally distinguish high- from low-pitched tones. Single
188 tones consisted of a 200 ms sine wave and double-tones consisted of two 70 ms sine waves
189 interspaced with 80 ms, which resulted in a 220 ms stimulus. Such durations made it impossible for
190 the triathletes to initiate any decision process before they had heard the entire stimulus.

191 It is well established that perceived loudness depends on tone (15, 37) and duration (33, 34).
192 Single and double, high- and low-pitched tones amplitudes were adjusted in accordance to equal-
193 loudness contours (often referred to as Fletcher-Munson curves) so that they met the international
194 standard ISO 226 specifications (ISO 2012). During the medical assessment, subjects underwent an
195 audiogram to ensure none of them had any hearing impairment.

196 The 30 stimuli were introduced in random order into a 90 s mp3 file and were separated with a
197 random duration such that two consecutive stimuli were interspaced by at least 500 ms. A different file
198 was played for each running stage so that it was not possible for the subject to learn the stimuli
199 arrangement inside a file.

200 Data were processed in OriginPro 8.1 (OriginLab, Northampton, MA) with a custom-written
201 script that returned, for each running stage, the percentage of false answers (excluded < 200 ms).

202

203 *Questionnaires.* The effect of the training regimen was also recorded through the assessment
204 of the *perceived sensations* of subjects. The subjects were tested at rest and during the maximal
205 incremental tests.

206 The Mindeval system was used to collect the data at rest (Mindeval GydléInc. Québec,
207 CANADA). It is comprised of a web interface with a database and a stand-alone application. In the
208 Pre- and -Post conditions, participants entered their personal key and answered questions within three
209 areas related to pain, tiredness, and well-being, using a visual analogic scale. The software records the
210 location of the indicator with a number ranging between 0 (no pain) and 100 (maximum pain). The
211 collected data was stored on a secured server. Before the initiation of the study, triathletes were
212 accustomed to the software, and the questions relative to their subjective sensations were thoroughly
213 explained.

214 The rating of perceived exertion (RPE) was measured verbally using the Borg scale (3) during
215 the maximal running test. This scale measures the subjective sensations accompanying the exercise.
216 The scale and its purpose were carefully explained to each triathlete before each incremental test. The

217 triathletes were instructed to give a general RPE, a muscular RPE and a ventilatory RPE, immediately
218 at the end of each running step and at exercise cessation.

219

220 *Data and statistical analyses*

221

222 The effect of the training regimen was analysed using the magnitude of variation between the
223 beginning and the end of phase III for every parameter investigated. To reduce the effect of inter-
224 individual differences in performance level, subsequent analyses were performed for three relative
225 intensity levels of exercise determined for each triathlete at the end of phase III: low intensity running,
226 lactate threshold (LT) and at exhaustion. Each parameter was compared with its respective value
227 measured for the same running speed at the beginning of phase III. For all triathletes, the low intensity
228 running was set at 13 km·h⁻¹ because: i) A very low coefficient of variation of running speed was
229 indeed reported until this intensity (coefficient of variation of 3.93 and 2.24 at 12km·h⁻¹ and 13 km·h⁻¹,
230 respectively); ii) this running velocity was at least 2 km·h⁻¹ lower than LT for all triathletes.

231

232 Statistical analysis was performed using Statistica software for Windows (Statsoft, version
233 7.0, Statistica, Tulsa, Oklahoma, USA). For the statistical procedure, the level of significance was set
234 at $p < 0.05$.

235

236 *Assessment of the OR syndrome.* In order to determine the reproducibility of performance
237 during the maximal running test and to identify OR athletes in the IT group, ICC (intraclass
238 correlation coefficient) and confidence interval at 100% of performance variation were calculated for
239 the NT group. To be diagnosed as OR, athletes of the IT group had to reveal a performance decrement
240 higher than the lowest reproducibility value reported for the NT group (OR threshold). Using that
241 procedure, the IT group was divided in two subgroups. When the subjects of the IT group
242 demonstrated a performance decrement higher than OR threshold, they were considered truly
243 overreached (OR group). When this assumption was not confirmed at the end of the overload period,
244 they we were not considered overreached (n-OR group).

245

246

247

248 *Discriminant analyses*

249

250 Three stepwise discriminant analyses (DA) were conducted to determine the ability of the
251 different variables measured during exercise to distinguish between NT, n-OR and OR groups and
252 subsequently predict group membership. The criterion used to determine whether a variable entered
253 the model (i.e., discriminant function) was Wilk's Lambda, which measures the deviations within each

254 group with respect to the total deviations. The sample-splitting method initially included the variable
255 that most minimized the value of Wilk's Lambda, provided the value of F was greater than a certain
256 critical value. The next step was pairwise combination of the variables with one of them being the
257 variable included in the first step. Successive steps were performed in the same manner, always with
258 the condition that the F-value corresponding to the Wilk's Lambda of the variable to select has to be
259 greater than the aforementioned "entry" threshold. If this condition was not satisfied, the process was
260 halted, and no further variables were selected in the process. Before including a new variable, an
261 attempt was made to make some of those already selected if the increase in the value of Wilk's
262 Lambda was minimal, and the corresponding F-value was below a critical value. Wilk's Lambda,
263 canonical correlation index, and percentage of subjects were computed as indicators of OR predictive
264 capacity.

265

266 The first DA (DA1) was performed on all the tested subjects (NT, n-OR and OR groups: 24
267 subjects tested at 3 running intensities) using all the variables tested in the study (n = 21). It was used
268 to determine if some variables would allow to identify three groups of triathletes according to their
269 training regimen and their performance decrement during the protocol. The second DA (DA2)
270 excluded the n-OR group (NT and OR groups: 19 subjects at 3 running intensities, see below for the
271 justification of the 19 subjects) using all the variables measured (n = 21). This analysis was performed
272 to identify the most valuable variables in classifying triathletes of NT and OR groups as overreached
273 or not. The discriminating variables with their respective Wilk's lambdas and p-value, canonical
274 correlation (r_c) and classification percentage were noted. Considering that markers of OR should be
275 applicable in training practice (32), a third additional DA (DA3) was performed to investigate the
276 minimal number of variables allowing a reasonable discrimination between the OR and NT groups.

277

278 *Parameters evolution*

279

280 Since this protocol involved a relatively small number of subjects (n < 32) and the data
281 obtained did not always meet the assumptions of normality, as assessed visually by normal probability
282 plot and by the Shapiro-Wilk test, non-parametric statistical analyses ensued. A Friedman rank test
283 was undertaken to evaluate the statistical differences in time for each group and a Mann-Whitney test
284 was completed to assess significant differences between NT and OR groups. The results are expressed
285 as the mean value with standard deviation (\pm SD).

286

287

288 **RESULTS**

289

290 All the subjects successfully completed the prescribed training program in both NT and IT
291 groups.

292

293 *Assessment of the OR syndrome*

294

295 An intra-class correlation test (ICC) was used to classify the subjects from the IT group as
296 overreached (OR group) or non-overreached (n-OR group). First, the reproducibility of the
297 performance of the NT group was measured using the ICC test (see method). ICC value was very high
298 (ICC = 0.98), with a performance repeatability ranging between 0.6 to 1.8% (mean: 0.9%). On the
299 basis of this analysis, a decrement of performance of greater than 1.8% was used as the criteria to
300 discriminate the OR subjects in the IT group. Subsequent analysis showed that only 11 of the 16
301 triathletes that complete the overload training were considered as truly OR group). The five other
302 subjects of the IT group were not diagnosed OR.

303

304 *Performance*

305

306 In the OR group, the running performance decreased on average by $4.4 \pm 1.1\%$ between the
307 beginning and the end of the intensified training period ($18.3 \pm 0.2 \text{ km}\cdot\text{h}^{-1}$ and $17.6 \pm 0.3 \text{ km}\cdot\text{h}^{-1}$, $p <$
308 0.001 , pre- and post-overload period, respectively). When expressed in total running distance covered
309 during the incremental test, this decline represented $13.3 \pm 3.2\%$.

310

311 *Physiological parameters*

312

313 Both the NT and OR groups were first submitted to the same initial 4 week training protocol
314 (phases I and II in Figure 1). As shown in Table 2, the physiological variables values measured at the
315 end of phase II were not significantly different between the two experimental groups. The OR group
316 then completed a training program with 40% increase in load (phase III).

317

318 *Metabolic parameters.* At the end of the overload period (phase III), a decrease of HR and $[\text{La}^-]$
319 $_{\text{b}}$ values was observed for the OR group for the two submaximal intensities and at exhaustion (Table
320 2a). In contrast, no significant variation was observed for these two parameters for the three running
321 intensities in the NT group. These variations in HR and $[\text{La}^-]_{\text{b}}$ values were significantly different for
322 OR and NT groups for all the running intensities (compare the numerical values in columns 3 and 6 of
323 Table 2a). No significant differences in $\dot{V}\text{O}_2$ and \dot{V}_{E} values were observed between the two groups
324 before and after phase III.

325

326 *Blood parameters.* No significant statistical difference in [CK] was observed in the OR group
327 during phase III (234 ± 142 and 257 ± 157 UI.L⁻¹, pre- and post- phase III, $p = 0.07$). No significant
328 variation was observed either in the NT group for this parameter during the same period (180 ± 83 and
329 161 ± 49 UI.L⁻¹, pre- and post- phase III, respectively, $p = 0.48$). Similarly, there were no significant
330 differences in plasma catecholamine concentrations in both groups before and after phase III ($p >$
331 0.37). Similarly, there were no significant interaction (time x training regimen) for plasma [CK] ($p =$
332 0.17), adrenalin ($p = 0.88$) and noradrenalin ($p = 0.90$) at rest.

333

334 *Cognitive performance*

335

336 There was no difference between groups at rest ($-5.5 \pm 11.2\%$, $-4.3 \pm 3.4\%$, for NT and OR
337 groups, respectively, $p = 0.39$), low intensity ($-1.2 \pm 4.5\%$, $-2.0 \pm 5.5\%$, for NT and OR groups,
338 respectively, $p = 0.69$) and lactate threshold ($-1.9 \pm 8.7\%$, $1.3 \pm 9.2\%$, for NT and OR groups,
339 respectively, $p = 0.52$). In contrast, the OR group demonstrated a significant decrease in performance
340 at exhaustion than the NT group ($8.7 \pm 11.3\%$ and $-12.1 \pm 17.9\%$, for NT and OR groups, respectively,
341 $p = 0.04$).

342

343 *Biomechanical parameters*

344

345 Except dS (support duration) at LT (lactate threshold) (-11 ± 12 ms and 2 ± 6 ms, for OR and
346 NT groups, respectively, $p = 0.01$), no significant interaction effect was reported for all the 9
347 parameters investigated at three running speeds ($p > 0.05$) (Table 2b).

348

349 *Perceived sensations*

350

351 *At rest*

352

353 The OR triathletes reported increased sensations of pain (16 ± 24 and 53 ± 26 , $p < 0.01$, before
354 and after the overload period, respectively) and tiredness (20 ± 18 and 85 ± 11 , $p < 0.001$, before and
355 after the overload period, respectively). In contrast, there was no significant difference for these two
356 parameters during the same period for the NT group (28 ± 32 and 18 ± 13 , for pain, 38 ± 16 and $38 \pm$
357 24 , for tiredness, before and after phase III, respectively, $p > 0.05$). There was a significant difference
358 in the change in pain ($p = 0.03$) and tiredness ($p < 0.001$) between the OR and NT groups. Well being
359 sensation demonstrated no significant change in both groups before and after phase III (76 ± 17 and 61
360 ± 31 , $p = 0.23$, for OR group, 73 ± 22 and 73 ± 20 , $p = 0.72$, before and after the overload period,
361 respectively).

362

363 *During exercise*

364

365 There was a significant difference in ΔGenRPE (general perceived exertion change) was
366 observed at exhaustion ($+1.8 \pm 1.4$ and $+0.1 \pm 1.3$, $p = 0.02$) between the OR and NT groups, however
367 there were no-statistical differences at low ($+2.1 \pm 3.1$ and -0.4 ± 1.0 , $p = 0.05$) and LT intensities
368 ($+2.2 \pm 2.4$ and $+0.1 \pm 1.8$, $p = 0.08$). The $\Delta\text{MuscRPE}$ (muscular perceived exertion change) was
369 significantly different between NT and OR groups at Low ($+4.1 \pm 3.2$ and $+0.0 \pm 1.0$, $p < 0.01$) and
370 LT intensities ($+3.3 \pm 2.2$ and $+0.8 \pm 1.1$, $p = 0.02$), but not at exhaustion ($+3.3 \pm 2.0$ and $+1.7 \pm 1.4$, p
371 $= 0.10$). Finally, the training load did not influence $\Delta\text{VentRPE}$ (ventilatory perceived exertion change)
372 for the three running intensities ($p > 0.20$).

373

374 *Discriminant analyses*

375

376 The DA1 was performed on all the tested subjects using all the variables tested in the study. It
377 was used in order to determine if some variables would allow identification of three groups of
378 triathletes according to their training regimen and performance decrement during the protocol. DA1
379 indicated the presence of two significant discriminant functions ($p < 0.01$). As a linear combination of
380 discriminating variables, the analysis resulted in canonical coefficients for the first function being
381 derived so that the group means on the function were as different as possible. The coefficient for the
382 second function was also derived to maximize the differences between the group means as long as the
383 values on the second function were not correlated with those on the first function. The discriminant
384 functions were used to compute the position of the triathlete's data in the discriminant space (Figure
385 2). The horizontal direction corresponded to function 1, with the lateral separation among the three
386 groups indicating how much they were distinguished on this function. The vertical axis corresponded
387 to function 2, with the vertical separation indicating the manner in which the groups were
388 distinguished in a way unrelated to the way they were separated on function 1 (40). Using this analysis
389 87.5% of the NT, n-OR and OR subjects were classified in the correct group (Table 3). With three
390 groups, 33.3% of correct predictions are possible with pure random assignment (24). In summary,
391 DA1 showed that we could discriminate the three groups of athletes using the variables measured.

392

393 The second DA (DA2) excluded the n-OR group using all the variables measured. It was
394 performed to identify the most valuable variables in classifying triathletes of NT and OR groups as
395 overreached or not. It indicated the presence of one significant discriminant function ($p < 0.001$). The
396 discriminant function was interpreted by examining the standardized coefficients (see Table 4a) in
397 order to ascertain which variables contributed most to determining scores on the function. The larger
398 the magnitude of the coefficient, the greater the contribution of that variable to the discriminant
399 function. ΔHR (heart rate variation) made the greatest contribution to scores on that function followed

400 by ΔdS (stance phase duration change), ΔdA (aerial phase duration change), $\Delta[La^-]_b$ (blood lactate
401 concentration change) and ΔLxn (step-length change) with a lesser contribution from the three other
402 factors selected in the model ($\Delta PImn$, propulsive impulse change; ΔLyn , step largeness change;
403 $\Delta muscRPE$, muscular perceived exertion change). The classification procedure correctly placed 98.2%
404 of the triathletes of NT and OR groups into their respective groups (see Table 4b). The probability by
405 chance with two groups would have been 50.0%. The extent to which all parameters were valuable
406 and necessary in DA2 was determined via a stepwise procedure. A forward stepwise procedure was
407 utilized whereby the individual variable that provided the greatest univariate discrimination was
408 selected first and was then paired with each of the remaining variables one at a time, to determine the
409 combination which produced the greatest discrimination. This analysis included the 8 selected
410 variables of DA2 in the following order of decreasing discriminating power: ΔHR , $\Delta[La^-]_b$, $\Delta PImn$,
411 ΔdS , ΔdA and ΔLxn . All these variables made a significant ($p < 0.05$) contribution to discrimination
412 between NT and OR groups, while no statistical significant contribution were observed for both ΔLxn
413 and $\Delta MuscRPE$ (Table 4c). In summary, DA2 ranked 8 of the 21 variables measured as valuable to
414 discriminate between OR and NT groups.

415

416 Considering that only a limited number of markers of OR could practically be applied in the
417 training environment, a third additional DA (DA3) was performed. It investigated the minimal number
418 of variables allowing a reasonable discrimination between the OR and NT groups. When the variables
419 was restricted to ΔHR and $\Delta[La^-]_b$ (i.e., the two most valuable variables in DA2), the classification
420 score still reached 89.5% (Table 5). The classification function coefficients determined by DA3 could
421 be used in an equation to determine the likelihood of an individual triathlete to be classified as OR
422 using variables measured during exercise:

423

$$424 \text{ OR index} = 0.17 \times \Delta HR + 0.89 \times \Delta[La^-]_b + 1.36$$

425

426 Where ΔHR and $\Delta[La^-]_b$ represent heart rate and blood lactate concentration changes, respectively. As
427 illustrated in Figure 2, using that formalism, a negative value strongly suggests a state of OR.

428

429

430 **DISCUSSION**

431

432 The main findings of this study were that: (i) Combining physiological, biomechanical and
433 cognitive variables were useful to assess overreaching (OR) in endurance trained athletes after an
434 overload period; (ii) multidimensional analysis showed that heart rate and blood lactate concentration
435 changes were the most important factors in discriminating between control and OR athletes; (iii) while
436 motor control did not appear to be altered during an incremental running test with OR, cognitive

437 performance was impaired at exhaustion in OR subjects compared to the controls; (iv) the
438 physiological perturbations associated with OR were coherent with perturbations of the autonomic
439 nervous system activity; (v) these results led to the proposal that an index based on two variables
440 could assist in the diagnosis of OR in endurance athletes.

441

442 At the end of the overload training period, a 4.4% decline in maximal running speed was
443 observed in the OR group. Given that the daily variation of this test was <1.8% in the NT group, the
444 decline in performance could be attributed to the effects of the intensified training protocol. This
445 reduction in performance was in line with the 5.4% decrement reported by Halson et al. (17) in OR
446 cyclists with a similar incremental protocol. When expressed in total running distance during the
447 incremental test, this decrease in performance represented 13.3% in the OR group. A similar decrease
448 was observed by Lehmann et al. (26), who showed an 8% decline in total running distance during an
449 incremental exercise test in middle- and long-distance runners. Additionally, in our study, the OR
450 triathletes reported a large increase in perceived fatigue at rest, while no significant variations were
451 assessed in the NT group. Reduced physical performance and increased fatigue are two of the common
452 criteria for diagnosing OR (18), which confirmed that these athletes were not adapting to the
453 prescribed overload training. It allowed us to conduct further comparison with the NT athletes (i.e.,
454 normal training group) to determine discriminate markers of OR/OT.

455

456 **Early detection of overreaching**

457

458 The aim of this study was to identify specific marker(s) of OR in triathletes that could be used
459 prospectively to prevent endurance athletes from developing OT. The present results showed that a
460 combination of 8 physiological, cognitive and biomechanical parameters changes measured during an
461 incremental maximal running test successfully discriminated between OR and NT triathletes at 98.2%
462 (chance probability: 50%). Indeed, with the exception of only 1/57 cases (19 triathletes, 3 running
463 intensities), the training state of individual athletes was adequately classified. Interestingly, the
464 stepwise discriminant analysis indicated that the ΔHR and $\Delta[\text{La}^-]_b$ were the two most valuable factors
465 to discriminate between OR and NT groups. When the discriminant analysis was restricted to these
466 two parameters, 89.5% of the triathletes were still well classified. These findings have strong practical
467 applications as both these measures fulfil the criteria defining a usable marker for detecting OR (and
468 OT) (32): (i) objective; (ii) not easily manipulated; (iii) applicable in training practice; (iv) not too
469 demanding for athletes; (v) affordable for the majority of athletes and (vi) based on a theoretical
470 framework.

471

472 We expected that alterations of the running motor patterns (i.e. stride kinematic and
473 mechanical parameters) in triathletes could have been a valid indicator of OR. Surprisingly, we were

474 only able to detect minor modifications in the motor pattern, which used in isolation, did not
475 distinguish OR athletes from the NT group. These observations suggest that motor control was largely
476 preserved during the incremental exercise (at submaximal levels), regardless of training status. These
477 findings may also partly explain why athletes can become OR/OT despite close and regular
478 observation from coaches. Indeed, without clearly visible changes in motor patterns (i.e. noticeable
479 changes gait), it becomes difficult to discriminate OR from other potential causes of performance
480 decrement, which emphasizes the necessity for regular monitoring in endurance athletes, especially
481 during periods of heavy training (43). On the basis of the present findings, we suggest to monitor HR
482 and blood lactate concentration. Indeed, the combination of these two measures in the OR index
483 algorithm ($OR\ index = 0.17 \Delta HR + 0.88 \Delta [La^-]_b + 1.36$), could be used as an objective early warning
484 for maladaptive training in endurance athletes.

485

486 **Underlying mechanisms of overreaching**

487

488 *The autonomic hypothesis*

489 Whilst the underlying cause(s) of OR (and OT) in endurance athlete remains to be determined
490 (18, 45), there is an agreement that the concomitant decrease of HR and $[La^-]_b$ reported in several
491 studies could reveal a down-regulation of the sympathetic nervous system and/or changes in
492 parasympathetic/sympathetic tone during OR (19, 26, 43). Two mutually non-exclusive mechanisms
493 (i.e. centrally and peripherally mediated factors) have been suggested to underpin these physiological
494 changes. In favor of a centrally mediated factors, Lehmann et al. (26) reported decreased nocturnal
495 urinary norepinephrine and epinephrine excretion after an increase in training volume leading to OR.
496 There was also a concomitant decline in submaximal and maximal heart rates along with the changes
497 in catecholamines. In contrast, others reported decreases in heart rate and/or (20) lactate concentration
498 in absence of catecholamine modulations (17, 43). Prolonged exposure to catecholamines resulting
499 from intensified training and/or psychological stress may also downregulate β -adrenergic receptors
500 sensitivity, and/or decrease their number (27, 47). This has been observed after exhaustive dynamic
501 exercise (6), chronic exposure to hypoxia (14) and during a prolonged long-term period of heavy
502 endurance training (23) or after infusion of adrenergic agonists (42).

503

504 *A role for cognitive factors?*

505 In the present study, the cognitive performance was preserved in all athletes at rest and
506 submaximal intensities. Notably however, cognitive performance was reduced at exhaustion in OR
507 athletes. These findings show that whilst cognitive measures were only marginally useful to predict
508 OR, they were affected by OR. These observations are consistent with the threshold theory that
509 involves two hypothetical notions (38). The first suggests that the brain has a reserve capacity and
510 second that the brain has a threshold of impairment. According to this model, the larger the brain

511 reserve capacity and the higher the threshold of impairment, the better the tolerance of cognitive
512 processes to different stimuli. In the context of that theory, we propose that the psychological load
513 associated with running during the incremental test (i.e., rate of perceived exertion, RPE) only affected
514 cognitive performance when high running speed were reached (i.e., beyond the lactate threshold). The
515 decreased cognitive performance observed at exhaustion was in agreement with Chmura and Nazar
516 (8), who demonstrated that it is only above lactate threshold that reaction time increased markedly
517 during a running incremental test.

518 The coincidence of increased physical exhaustion and the large deterioration in the double task
519 performance indicated that in OR and NT groups: (i) Running at severe intensities (i.e., above lactate
520 threshold), are accompanied by a large cognitive load; and (ii) that these two tasks rely upon the
521 similar cognitive resources. Moreover, since the cognitive performance showed greater decrease in the
522 OR triathletes (despite lower running speed at exhaustion) than the control group and this occurred
523 with an increase of both general and muscular perceived exertion, it seems that central factors may be
524 involved in OR. This is further supported by the finding that the increased perception of exertion was
525 not associated with higher muscle damage in the OR triathletes. Taken collectively, these results
526 demonstrate that the attention demand of running is increased at high intensity in OR subjects, which
527 may suggest a contribution of central fatigue in OR. These results agree with previous studies that
528 have highlighted similarities between OR/OT athletes with chronic fatigue syndrome and major
529 depression symptoms (2, 32). Indeed, decreased psychomotor speed has consistently been shown to be
530 present in both depression and OR/OT athletes (32). Furthermore, a reduced performance on
531 psychomotor speed tasks was observed in OT athletes at rest (1212, 13, 21, 31). The present
532 investigation extends these results by showing cognitive impairment during strenuous exercise in OR
533 athletes.

534

535 **Summary**

536 In order to determine discriminant markers of maladaptive training endurance athletes,
537 comparisons were made between various physiological, cognitive and biomechanical measures in OR
538 and non-OR triathletes during 3 weeks of increased training load. A combination of physiological,
539 cognitive and biomechanical parameters changes measured during an incremental maximal running
540 test successfully discriminated between OR and control at 98.2%. Heart rate and blood lactate
541 concentration variations were the two most discriminating factors (89.5% of discrimination success,
542 when combined).

543 The results showed that the triathletes running motor patterns were not altered until exhaustion
544 in OR subjects. These observations could explain why athletes can become OR/OT whilst under the
545 close supervision of a coach/scientist. Without visual marker, an external observer would have
546 difficulty to discriminate OR from other potential causes of performance decrement. These findings
547 also highlight that monitoring physiological responses could help preventing OR and OT. On the basis

548 of the current observations, we propose an OR index, which combines heart rate and blood lactate
549 concentration changes after a training period could be helpful to routinely detect OR in athletes
550 submitted to strenuous training regimen. Indeed, this algorithm may be used to monitor and
551 prospectively guide future manipulations in training load so that the risks of OR/OT are reduced.

552 Whilst the physiological mechanisms that underlie OR/OT remain to be fully elucidated, the
553 concomitant decrease of heart rate and blood lactate concentration changes pointed to perturbations of
554 the autonomic nervous system as one mechanism underlying the genesis of OR. Additionally, since
555 the double task showed that running at severe intensities was accompanied by an increased cognitive
556 load, which is further increased with OR, it also appears that an athlete's cognitive resources are
557 depleted during intense exercise with OR/OT. These results should be now confirmed on a larger
558 population of athletes, involved in different sports and levels of performance.

559

- 1 **Figure 1.** Schematic representation of the experimental protocol.
- 2 **Figure 2.** Discriminant analysis scatter plots using different number of groups and variables. NT:
- 3 normal training group; n-OR: intensified training group without overreaching symptoms; OR:
- 4 intensified training group with overreaching symptoms.
- 5

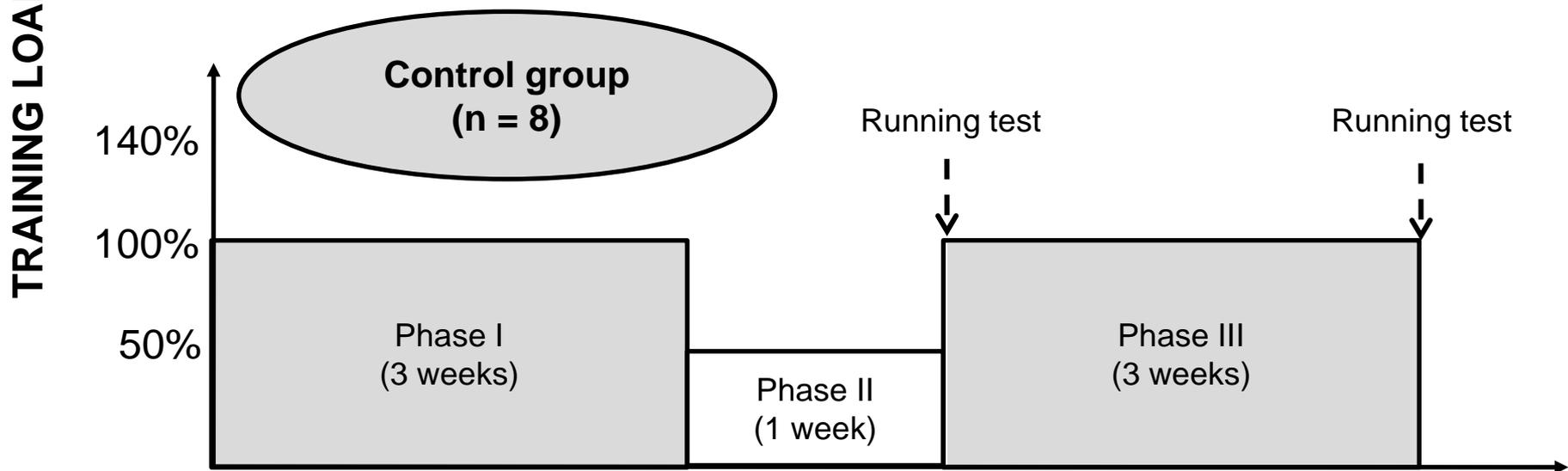
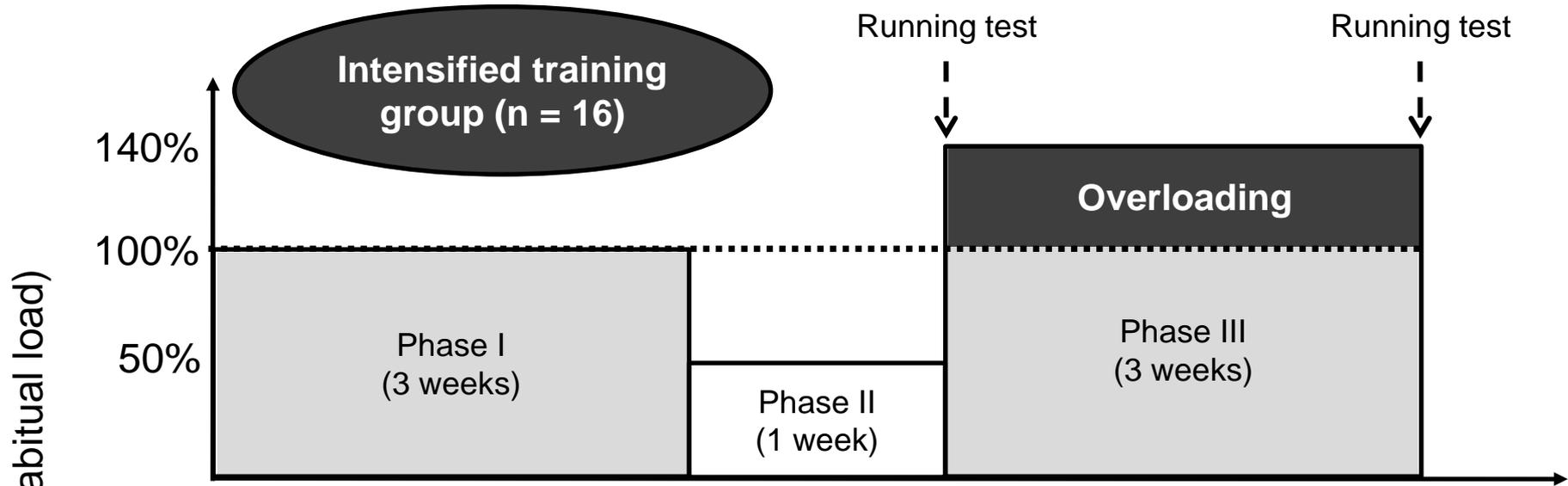
7 REFERENCES

8

- 9 1. **Adlercreutz H, Harkonen M, Kuoppasalmi K, Naveri H, Huhtaniemi I, Tikkanen**
10 **H, Remes K, Dessypris A, and Karvonen J.** Effect of training on plasma anabolic and
11 catabolic steroid hormones and their response during physical exercise. *International journal*
12 *of sports medicine* 7 Suppl 1: 27-28, 1986.
- 13 2. **Armstrong LE, and VanHeest JL.** The unknown mechanism of the overtraining
14 syndrome: clues from depression and psychoneuroimmunology. *Sports medicine* 32: 185-209,
15 2002.
- 16 3. **Borg G.** Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 2:
17 92-98, 1970.
- 18 4. **Bosquet L, Leger L, and Legros P.** Blood lactate response to overtraining in male
19 endurance athletes. *European journal of applied physiology* 84: 107-114, 2001.
- 20 5. **Bosquet L, Merkari S, Arvisais D, and Aubert AE.** Is heart rate a convenient tool to
21 monitor over-reaching? A systematic review of the literature. *British journal of sports*
22 *medicine* 42: 709-714, 2008.
- 23 6. **Brodde OE, Daul A, and O'Hara N.** Beta-adrenoceptor changes in human
24 lymphocytes, induced by dynamic exercise. *Naunyn-Schmiedeberg's archives of*
25 *pharmacology* 325: 190-192, 1984.
- 26 7. **Cheng B, Kuipers H, Snyder AC, Keizer HA, Jeukendrup A, and Hesselink M.** A
27 new approach for the determination of ventilatory and lactate thresholds. *International*
28 *journal of sports medicine* 13: 518-522, 1992.
- 29 8. **Chmura J, and Nazar K.** Parallel changes in the onset of blood lactate accumulation
30 (OBLA) and threshold of psychomotor performance deterioration during incremental exercise
31 after training in athletes. *International journal of psychophysiology : official journal of the*
32 *International Organization of Psychophysiology* 75: 287-290, 2010.
- 33 9. **Costill DL, Flynn MG, Kirwan JP, Houmard JA, Mitchell JB, Thomas R, and**
34 **Park SH.** Effects of repeated days of intensified training on muscle glycogen and swimming
35 performance. *Medicine and science in sports and exercise* 20: 249-254, 1988.
- 36 10. **Coutts AJ, Slatery KM, and Wallace LK.** Practical tests for monitoring
37 performance, fatigue and recovery in triathletes. *Journal of science and medicine in sport /*
38 *Sports Medicine Australia* 10: 372-381, 2007.
- 39 11. **Duffield R, Dawson B, Pinnington HC, and Wong P.** Accuracy and reliability of a
40 Cosmed K4b2 portable gas analysis system. *Journal of science and medicine in sport / Sports*
41 *Medicine Australia* 7: 11-22, 2004.
- 42 12. **Dupuy O, Lussier M, Fraser S, Bherer L, Audiffren M, and Bosquet L.** Effect of
43 overreaching on cognitive performance and related cardiac autonomic control. *Scandinavian*
44 *journal of medicine & science in sports* 2012.
- 45 13. **Dupuy O, Renaud M, Bherer L, and Bosquet L.** Effect of functional overreaching
46 on executive functions. *International journal of sports medicine* 31: 617-623, 2010.
- 47 14. **Favret F, and Richalet JP.** Exercise and hypoxia: the role of the autonomic nervous
48 system. *Respiratory physiology & neurobiology* 158: 280-286, 2007.
- 49 15. **Fletcher H, and Munson WA.** Loudness, Its Definition, Measurement and
50 Calculation. *J Acoust Soc Am* 5: 82-108, 1933.
- 51 16. **Fry RW, Morton AR, Garcia-Webb P, Crawford GP, and Keast D.** Biological
52 responses to overload training in endurance sports. *European journal of applied physiology*
53 *and occupational physiology* 64: 335-344, 1992.

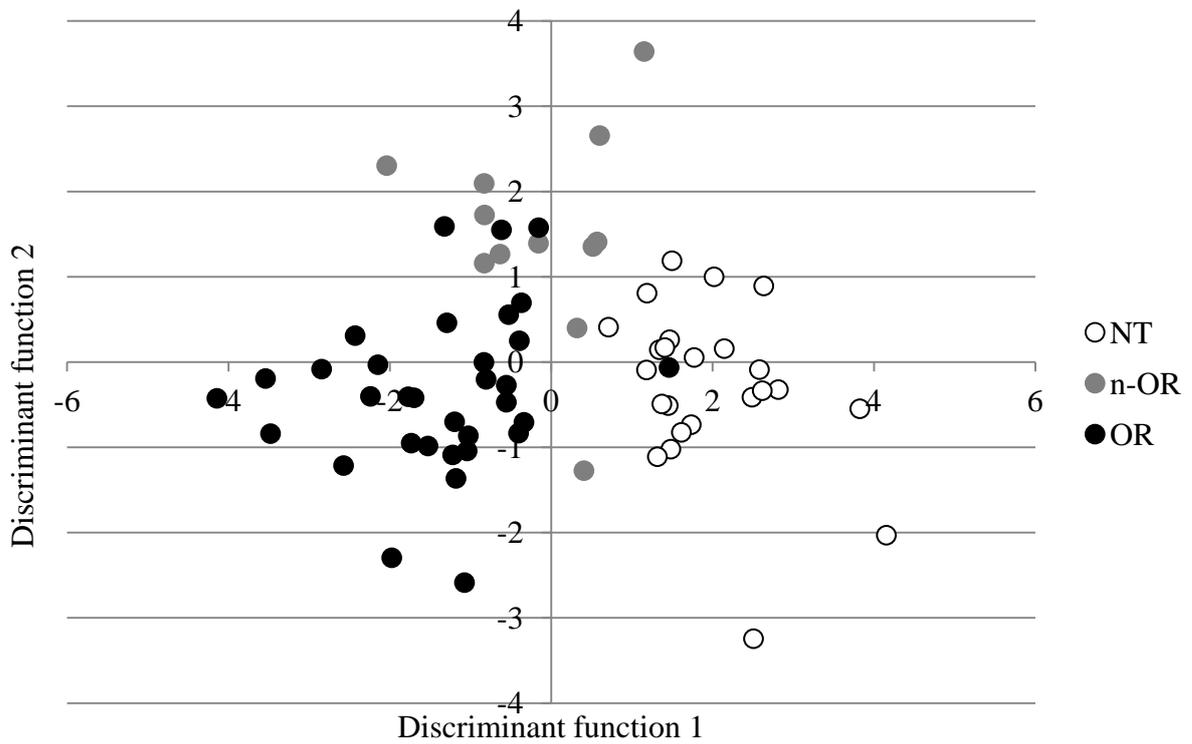
- 54 17. **Halson SL, Bridge MW, Meeusen R, Busschaert B, Gleeson M, Jones DA, and**
55 **Jeukendrup AE.** Time course of performance changes and fatigue markers during intensified
56 training in trained cyclists. *Journal of applied physiology* 93: 947-956, 2002.
- 57 18. **Halson SL, and Jeukendrup AE.** Does overtraining exist? An analysis of
58 overreaching and overtraining research. *Sports medicine* 34: 967-981, 2004.
- 59 19. **Hedelin R, Kentta G, Wiklund U, Bjerle P, and Henriksson-Larsen K.** Short-term
60 overtraining: effects on performance, circulatory responses, and heart rate variability.
61 *Medicine and science in sports and exercise* 32: 1480-1484, 2000.
- 62 20. **Hedelin R, Wiklund U, Bjerle P, and Henriksson-Larsen K.** Cardiac autonomic
63 imbalance in an overtrained athlete. *Medicine and science in sports and exercise* 32: 1531-
64 1533, 2000.
- 65 21. **Hynynen E, Uusitalo A, Konttinen N, and Rusko H.** Cardiac autonomic responses
66 to standing up and cognitive task in overtrained athletes. *International journal of sports*
67 *medicine* 29: 552-558, 2008.
- 68 22. **Jeukendrup AE, Hesselink MK, Snyder AC, Kuipers H, and Keizer HA.**
69 Physiological changes in male competitive cyclists after two weeks of intensified training.
70 *International journal of sports medicine* 13: 534-541, 1992.
- 71 23. **Jost J, Weiss M, and Weicker H.** Comparison of sympatho-adrenergic regulation at
72 rest and of the adrenoceptor system in swimmers, long-distance runners, weight lifters,
73 wrestlers and untrained men. *European journal of applied physiology and occupational*
74 *physiology* 58: 596-604, 1989.
- 75 24. **Klecka WR.** Discriminant Analysis. In: *Quantitative Applications in the Social*
76 *Sciences Series*, edited by Thousand Oaks CSage Publications, 1980.
- 77 25. **Lehmann M, Baumgartl P, Wiesenack C, Seidel A, Baumann H, Fischer S, Spori**
78 **U, Gendrisch G, Kaminski R, and Keul J.** Training-overtraining: influence of a defined
79 increase in training volume vs training intensity on performance, catecholamines and some
80 metabolic parameters in experienced middle- and long-distance runners. *European journal of*
81 *applied physiology and occupational physiology* 64: 169-177, 1992.
- 82 26. **Lehmann M, Dickhuth HH, Gendrisch G, Lazar W, Thum M, Kaminski R,**
83 **Aramendi JF, Peterke E, Wieland W, and Keul J.** Training-overtraining. A prospective,
84 experimental study with experienced middle- and long-distance runners. *International journal*
85 *of sports medicine* 12: 444-452, 1991.
- 86 27. **Lehmann M, Foster C, Dickhuth HH, and Gastmann U.** Autonomic imbalance
87 hypothesis and overtraining syndrome. *Medicine and science in sports and exercise* 30: 1140-
88 1145, 1998.
- 89 28. **Lehmann M, Mann H, Gastmann U, Keul J, Vetter D, Steinacker JM, and**
90 **Haussinger D.** Unaccustomed high-mileage vs intensity training-related changes in
91 performance and serum amino acid levels. *International journal of sports medicine* 17: 187-
92 192, 1996.
- 93 29. **Mackinnon LT, Hooper SL, Jones S, Gordon RD, and Bachmann AW.** Hormonal,
94 immunological, and hematological responses to intensified training in elite swimmers.
95 *Medicine and science in sports and exercise* 29: 1637-1645, 1997.
- 96 30. **Meeusen R, Duclos M, Gleeson M, Rietjens G, Steinacker J, and Urhausen A.**
97 Prevention, diagnosis and treatment of the Overtraining Syndrome. *Eur J Sport Sci* 6: 1-14,
98 2006.
- 99 31. **Nederhof E, Lemmink K, Zwerver J, and Mulder T.** The effect of high load
100 training on psychomotor speed. *International journal of sports medicine* 28: 595-601, 2007.
- 101 32. **Nederhof E, Lemmink KA, Visscher C, Meeusen R, and Mulder T.** Psychomotor
102 speed: possibly a new marker for overtraining syndrome. *Sports medicine* 36: 817-828, 2006.

- 103 33. **Pedersen OJ, Lyregaard PE, and Poulsen TE.** The round robin test on evaluation of
104 loudness level of impulsive noise 1977.
- 105 34. **Port E.** Über die Lautstärke einzelner kurzer Schallimpulse. *Acustica* 212-223, 1963.
- 106 35. **Purvis D, Gonsalves S, and Deuster PA.** Physiological and psychological fatigue in
107 extreme conditions: overtraining and elite athletes. *PM & R : the journal of injury, function,*
108 *and rehabilitation* 2: 442-450, 2010.
- 109 36. **Pyne DB, Boston T, Martin DT, and Logan A.** Evaluation of the Lactate Pro blood
110 lactate analyser. *European journal of applied physiology* 82: 112-116, 2000.
- 111 37. **Robinson DW, and Dadson RS.** A re-determination of the equal-loudness relations
112 for pure tones. *Brit J Appl Phys* 7: 166-181, 1956.
- 113 38. **Satz P.** Brain reserve capacity on symptom onset after brain injury: a formulation and
114 review of evidence for threshold theory *Neuropsychol* 7: 273-295, 1993.
- 115 39. **Snyder AC, Kuipers H, Cheng B, Servais R, and Fransen E.** Overtraining
116 following intensified training with normal muscle glycogen. *Medicine and science in sports*
117 *and exercise* 27: 1063-1070, 1995.
- 118 40. **Stevens J.** *Applied Multivariate Statistics for the Social Sciences.* Hillsdale: 1992.
- 119 41. **Thomas L, and Busso T.** A theoretical study of taper characteristics to optimize
120 performance. *Medicine and science in sports and exercise* 37: 1615-1621, 2005.
- 121 42. **Tohmeh JF, and Cryer PE.** Biphasic adrenergic modulation of beta-adrenergic
122 receptors in man. Agonist-induced early increment and late decrement in beta-adrenergic
123 receptor number. *The Journal of clinical investigation* 65: 836-840, 1980.
- 124 43. **Urhausen A, Gabriel HH, and Kindermann W.** Impaired pituitary hormonal
125 response to exhaustive exercise in overtrained endurance athletes. *Medicine and science in*
126 *sports and exercise* 30: 407-414, 1998.
- 127 44. **Urhausen A, Gabriel HH, Weiler B, and Kindermann W.** Ergometric and
128 psychological findings during overtraining: a long-term follow-up study in endurance
129 athletes. *International journal of sports medicine* 19: 114-120, 1998.
- 130 45. **Urhausen A, and Kindermann W.** Diagnosis of overtraining: what tools do we
131 have? *Sports medicine* 32: 95-102, 2002.
- 132 46. **Uusitalo AL, Huttunen P, Hanin Y, Uusitalo AJ, and Rusko HK.** Hormonal
133 responses to endurance training and overtraining in female athletes. *Clinical journal of sport*
134 *medicine : official journal of the Canadian Academy of Sport Medicine* 8: 178-186, 1998.
- 135 47. **Zavorsky GS.** Evidence and possible mechanisms of altered maximum heart rate with
136 endurance training and tapering. *Sports medicine* 29: 13-26, 2000.
- 137
- 138



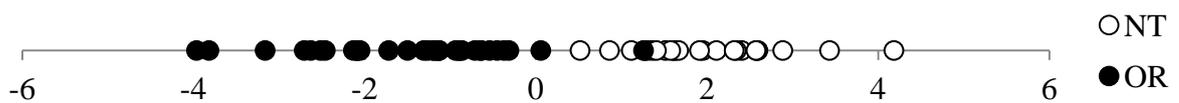
A. Discriminant analysis 1 (3 groups, 16 variables)

Success rate for classification : 87.5%



b. Discriminant analysis 2 (2 groups, 16 variables)

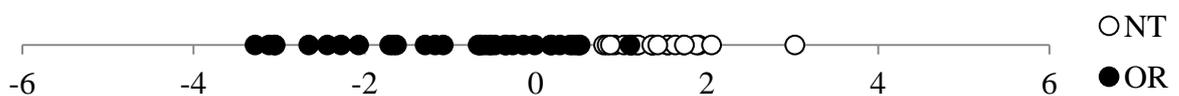
Success rate for classification : 98.2%



c. Discriminant analysis 3 (2 groups, 2 variables)

Success rate for classification : 89.5%

$$\text{OR index} = 0.17 \Delta\text{HR} + 0.88 \Delta[\text{La}^-]_b + 1.36$$



Subject characteristics	Normal Training group (n = 8)	Intensified Training group (n = 15)
Age (years)	32.4 ± 2.8	31.0 ± 1.4
Height (cm)	176.8 ± 2.1	178.7 ± 1.2
Weight (kg)	69.7 ± 2.6	70.6 ± 1.3
$\dot{V}O_{2max}$ (ml.min⁻¹.kg⁻¹)	64.9 ± 2.8	62.3 ± 1.5
MAS (km.h⁻¹)	18.2 ± 0.4	18.3 ± 0.2

Table 1. Selected characteristics of the two experimental groups. $\dot{V}O_{2max}$: maximal oxygen uptake; MAS: maximal aerobic speed. Values are expressed as means ± SEM of the means. No significant difference between both groups for all the parameters.

a.

Intensity	Physiological variables	Normal Training Group (NT, n = 8)			Overreached Group (OR, n = 11)		
		Pre-Training	Post-Training	Variation	Pre-Training	Post-Training	Variation
Low	$\dot{V}O_2$ ($\text{mlO}_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$)	48.8 ± 5.0	47.9 ± 5.2	-0.9 ± 2.4	49.1 ± 1.8	49.7 ± 3.3	0.6 ± 2.1
	\dot{V}_E ($\text{L} \cdot \text{min}^{-1}$)	92 ± 14	90 ± 13	-2 ± 5	91 ± 11	94 ± 12	3 ± 5
	HR ($\text{beats} \cdot \text{min}^{-1}$)	155 ± 11	154 ± 11	-1 ± 2	152 ± 13	143 ± 13**	-8 ± 6[#]
	$[\text{La}]_b$ ($\text{mmol} \cdot \text{L}^{-1}$)	1.7 ± 0.5	1.5 ± 0.4	-0.2 ± 0.3	2.7 ± 1.0	1.9 ± 0.8**	-0.8 ± 0.8[#]
LT	$\dot{V}O_2$ ($\text{mlO}_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$)	58.5 ± 3.4	58.5 ± 1.5	0.0 ± 0.6	57.4 ± 3.9	57.9 ± 6.0	0.4 ± 3.0
	\dot{V}_E ($\text{L} \cdot \text{min}^{-1}$)	130 ± 19	131 ± 14	1 ± 8	126 ± 17	130 ± 19	4 ± 5
	HR ($\text{beats} \cdot \text{min}^{-1}$)	176 ± 8	175 ± 8	-1 ± 3	172 ± 9	163 ± 9**	-9 ± 5^{##}
	$[\text{La}]_b$ ($\text{mmol} \cdot \text{L}^{-1}$)	3.4 ± 0.8	3.1 ± 0.8	-0.2 ± 0.6	3.8 ± 1.1	2.5 ± 0.7**	-1.3 ± 0.8[#]
At exhaustion	$\dot{V}O_2$ ($\text{mlO}_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$)	61.5 ± 3.3	61.3 ± 1.6	-0.2 ± 1.2	61.0 ± 5.2	60.9 ± 6.4	-0.1 ± 3.2
	\dot{V}_E ($\text{L} \cdot \text{min}^{-1}$)	154 ± 17	159 ± 15	5 ± 11	162 ± 22	161 ± 23	-1 ± 11
	HR ($\text{beats} \cdot \text{min}^{-1}$)	182 ± 13	182 ± 12	0 ± 1	181 ± 8	173 ± 8***	-8 ± 3^{###}
	$[\text{La}]_b$ ($\text{mmol} \cdot \text{L}^{-1}$)	8.9 ± 1.1	9.0 ± 0.7	0.3 ± 0.6	8.1 ± 2.0	6.9 ± 1.7**	-1.2 ± 0.2^{##}

b.

Intensity	Biomechanical parameters	Normal Training Group (n = 8)			Overreached Group (n = 11)		
		Pre-Training	Post-Training	Variation	Pre-Training	Post-Training	Variation
Low	Stride length (x leg length)	1.39 ± 0.06	1.40 ± 0.08	0.01 ± 0.05	1.36 ± 0.05	1.36 ± 0.06	0.00 ± 0.03
	Support duration (ms)	243 ± 11	241 ± 18	-2 ± 10	255 ± 17	253 ± 13	-1 ± 8
	Aerial duration (ms)	112 ± 20	116 ± 21	-1 ± 10	104 ± 26	104 ± 22	-1 ± 10
	Maximum peak vertical force (x weight)	2.63 ± 0.24	2.65 ± 0.25	0.02 ± 0.07	2.52 ± 0.16	2.50 ± 0.15	-0.02 ± 0.07
LT	Stride length (x leg length)	1.65 ± 0.10	1.63 ± 0.11	-0.02 ± 0.04	1.56 ± 0.10	1.54 ± 0.11	-0.02 ± 0.05
	Support duration (ms)	211 ± 12	211 ± 17	-1 ± 8	229 ± 15	231 ± 13	2 ± 7
	Aerial duration (ms)	130 ± 23	132 ± 24	2 ± 6	120 ± 25	108 ± 23	-11 ± 12^{##}
	Maximum peak vertical force (x weight)	2.83 ± 0.33	2.83 ± 0.34	0.00 ± 0.07	2.67 ± 0.21	2.60 ± 0.17	-0.07 ± 0.11
At exhaustion	Stride length (x leg length)	1.79 ± 0.11	1.76 ± 0.12	-0.03 ± 0.05	1.68 ± 0.14	1.68 ± 0.14	-0.01 ± 0.06
	Support duration (ms)	199 ± 10	198 ± 16	-1 ± 10	214 ± 15	208 ± 13	-7 ± 9
	Aerial duration (ms)	130 ± 20	131 ± 19	2 ± 3	120 ± 22	117 ± 20	-3 ± 10
	Maximum peak vertical force (x weight)	2.83 ± 0.29	2.84 ± 0.28	0.01 ± 0.08	2.70 ± 0.21	2.66 ± 0.18	-0.04 ± 0.12

Table 2. Mean values (\pm SD) and deltas of variation of selected physiological (a) and biomechanical parameters (b) at baseline and after the training period for the normal training group and the overreached group. The data are presented for three running intensities determined at the end of the training program: Low (13km.h⁻¹), Lactate Threshold (LT) and at exhaustion. Each parameter is presented for the same absolute running speed before and after the training period. $\dot{V}O_2$: oxygen uptake; $\dot{V}E$: expiratory flow; HR: heart rate; [La-]b: blood lactate concentration. Significantly different from pre-training at * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Significantly different from the normal training group at [#] $p < 0.05$; ^{##} $p < 0.01$; ^{###} $p < 0.001$.

Group	Number of cases	Predicted group			Correct
		NT	n-OR	OR	
NT	24	24	0	0	100%
n-OR	15	2	10	3	66.7%
OR	33	1	3	29	87.8%
Total	72	27	13	32	87.5%

Table 3. Classification matrix of discriminant analysis 1 using 3 groups and 21 variables (DA1). Each case represented one subject for one exercise intensity. NT: subjects of the normal training group; n-OR: subjects of the overload group demonstrating no clinical symptoms of overreaching; OR: subjects of the overreached group.

a.

Variable	Standardized coefficient
Δ HR	-0.74
Δ dS	-0.61
Δ dA	-0.58
Δ [La ⁻] _b	-0.47
Δ Lxn	-0.44
Δ PI _{mn}	-0.38
Δ Lyn	-0.26
Δ MuscRPE	0.23

b.

Group	Number of cases	Predicted group		Correct
		NT	OR	
NT	24	24	0	100%
OR	33	1	32	97.0%
Total	57	25	32	98.2%

c.

Step	Variable	Wilk's lambda	Significance level
1	Δ HR	0.39	0.0000
2	Δ [La ⁻] _b	0.31	0.005
3	Δ PI _{mn}	0.29	0.03
4	Δ dS	0.31	0.004
5	Δ dA	0.30	0.009
6	Δ Lxn	0.30	0.02
7	Δ Lyn	0.28	0.14
8	Δ MuscRPE	0.27	0.20

Table 4. Detailed results for the stepwise discriminant analysis using 2 groups and 21 variables (DA2): standardized canonical discriminant function coefficients (a); classification matrix (b) and summary table (c). NT: normal training group; OR: overreached group; HR: heart rate; [La⁻]_b: blood lactate concentration; PI_{mn}: normalised maximum peak vertical force; dS: support duration; dA: aerial duration; Lxn: normalised stride length; Lyn : normalised stride largeness; MuscRPE: muscular rate of perceived exertion.

Group	Number of cases	Predicted group		Correct
		NT	OR	
NT	24	23	1	95.8%
OR	33	5	28	84.8%
Total	57	28	29	89.5%

Table 5. Classification matrix of discriminant analysis using two groups and two variables (ΔHR , $\Delta [La^-]_b$, DA3). Each case represented one subject for one exercise intensity. NT: normal training group; OR: overreached group.