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Original

Identification of the plateau in maximal oxygen consumption: proposal and application of a new method of analysis

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ABSTRACT

Objective: The classic criterion for $VO_{2máx}$ plateau identification was proposed by Taylor et al. (1955), however, there are many critiques of this method. In this paper, we propose a new statistic-based VO_{2max} plateau identification methodology. In addition, we aim to test for eventual differences between characteristics of the individuals who presented and those who did not present the maximum VO_{2max} plateau.
Method: Forty-one (n = 41) physically active men participated. The subjects underwent a cardiopulmonary exercise test using ramp protocol to measure the VO_{2max} and other physiological variables. The identification of VO_{2max} plateau was performed by segmented linear regression with unknown breakpoints for each individual.
Results: Although 58.54% (24) of the sample presented VO_{2max} plateau, no significant differences were observed in metabolic, ventilatory and velocity variables between the groups.
Conclusion: The methodology presents advantages, since it is adequate to analyze VO_2 variations individually and because it is based on statistical techniques, which considers the continuous records of the maximal effort test, not segmenting it in sections for analysis. The comparison between groups, according to the occurrence of the plateau, showed no differences between them.
Keywords: Plateau; Maximal Oxygen Consumption; Physical fitness.

Identificación de la meseta en el consumo máximo de oxígeno: propuesta y aplicación de un nuevo método de análisis

RESUMEN

Objetivo: El criterio clásico para la identificación de la meseta lo propuso Taylor (1955), sin embargo, hay muchas críticas al método. Se plantea con este estudio presentar un nuevo método de identificación de la meseta de $VO_{2máx}$., basado en cálculos estadísticos. Además, se pretende con este estudio determinar si hay disconformidad entre las características de los individuos que presentaron y los que no presentaron la meseta de $VO_{2máx}$.
Método: Formaron parte del estudio cuarenta y un varones (n = 41) físicamente activos. Cada indivíduo hizo un examen cardiopulmonar en el cual fue utilizado un protocolo en rampa para medir el $VO_{2máx}$. y otras variables fisiológicas. La identificación de la meseta de $VO_{2máx}$. se produjo a través del análisis de regresión segmentada y con el punto de quiebre ignorado para cada individuo.
Resultados: Un total del 58.54% (24) de la muestra presentaron meseta de $VO_{2máx}$. Entre los grupos, no se observó diferencias significativas en las variables metabólicas, ventilatoria y de velocidad.
Conclusión: La metodología planteada presenta ventajas, ya que es eficaz para analizar individualmente las variaciones de VO_2, además de basarse en técnicas estadísticas que consideran a los registros de exámenes de esfuerzo máximo realizados, sin segmentarse para análisis. La comparación entre grupos, de acuerdo con lo sucedido en la meseta, no evidenció disconformidad entre los individuos.
Palabras clave: Meseta; Consumo Máximo de Oxígeno; Aptitud física.

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Identificação do platô no consumo máximo de oxigênio: proposta e aplicação de um novo método de análise

RESUMO

Objetivo: O criterio clássico para identificação de platô de VO$_{2máx}$ foi proposto por Taylor et al. (1955), no entanto, existem muitas críticas a esse método. O objetivo deste estudo é apresentar uma nova metodologia de identificação de platô no VO$_{2máx}$, baseada em cálculos estatísticos. Além disso, pretendemos identificar se há diferença entre as características dos indivíduos que apresentaram e os que não apresentaram o platô no VO$_{2máx}$.

Método: Quarenta e um (n = 41) homens fisicamente ativos participaram do estudo. Os indivíduos foram submetidos a um teste de exercício cardiopulmonar usando um protocolo de rampa para medir o VO$_{2máx}$ e outras variáveis fisiológicas. A identificação do platô do VO$_{2máx}$ foi realizada por meio de uma regressão linear segmentada com pontos de parada desconhecidos para cada indivíduo.

Resultados: Embora 58.54% (24) da amostra apresentassem o platô do VO$_{2máx}$, não foram observadas diferenças significativas nas variáveis metabólicas, ventilatórias e de velocidade entre os grupos.

Conclusão: A metodologia proposta apresenta vantagens, pois é adequada para analisar variações do VO$_2$ individualmente e por se basear em técnicas estatísticas, que consideram os registros contínuos do teste de esforço máximo, não segmentando em seções para análise. A comparação entre os grupos, de acordo com a ocorrência do platô, não mostrou diferenças entre eles.

Palavras-chave: Platô; Consumo Máximo de Oxigênio; Aptidão Física.

Introduction

The maximal oxygen consumption (VO$_{2max}$) is extensively used for evaluation of cardiorespiratory capacity and for prescription and monitoring of sports training.[1] The VO$_{2max}$ is usually obtained from the cardiopulmonary exercise test (CPET) performed with an incremental protocol in stepped or ramp load models.[2] Specifically, it has been observed a growth in the use of ramp protocol because it allows greater smoothness and individualization in the increase of load, since it is changed continuously and constantly in a given time interval. This avoids abrupt changes in recruitment of motor units or metabolic changes related to incremental protocols.[3]

The gold standard used for VO$_{2max}$ identification is the stabilization of the VO$_2$ behaviour at the end of the maximum test. The plateau is considered when the oxygen consumption stabilizes despite the load increase. The extent of this stabilization suggests that maximal cardiac output and maximal oxygen extraction have been achieved.[4-6] However, not all individuals develop a VO$_{2max}$ plateau at the end of the test, and there still is large variation of plateau incidence in literature (from 17% to 98%).[7] The explanation for this is related in the literature to the diversity of methodological delimitations.

Hill and Lupton[4] were the first to describe VO$_{2max}$ plateau. Corroborating with this concept, Taylor et al.[8] presented the most used criterion, which characterizes a plateau when it is observed variation smaller then 150 ml.min^{-1} or 2.1 ml.kg^{-1}.min^{-1} for a 2.5% increase in the treadmill slope. Although this method has been developed for other methodologies such as intermittent test protocol, long duration of the stages, several days for the application of the test and gas analysis by the Douglas bag technique, this criterion still is used for the ramp protocol. However, these methods are considered archaic, since the gas analyzers currently have high technology enabling measurement breath to breath of expired gas fractions.[9] Several authors have criticized this form of plateau identification showing in their studies that the plateau has low efficiency when applied to the ramp protocol.[2,10] Since there are differences between subjects in the variation of oxygen consumption (ΔVO$_2$) for any specific increase in exercise intensity, the criterion of the VO$_2$ plateau would only be valid if it was based on the individual slope of this variable in relation to the exercise intensity. However, most of the criteria used for plateau identification have been based on fixed intervals and considered the difference in VO$_2$ only between the last two stages of the maximal test.[11] Some authors have suggested criteria based on statistical methods to plateau identification as an alternative to incremental protocols, specifically for the ramp protocol.[11-14]

In view of the above discussion, it is necessary to propose a new statistical method for VO$_{2max}$ plateau identification, which jointly considers the test throughout its duration, be able to accommodate individual subjects characteristics and be applicable to the ramp test. Therefore, this study aims to fill this gap. As a secondary objective, it is intended to identify differences in the subject physical fitness characteristics who perform or not a VO$_{2max}$ plateau according to the proposed model.

Methods

Subjects

The study was cross-sectional observational and with a non-probabilistic sample of 41 physically active men. The eligibility criteria were: a) age between 18 and 40 years, b) to practice aerobic physical activity at least 3 times a week for 6 months or more. Exclusion criteria: a) cardiovascular, metabolic, respiratory or osteoligamentous disease, which limits the development of a maximum physical exercise; b) Use medications that interfere with the hemodynamic response and/or regular consumption of alcohol or tobacco. The subjects have been allocated in three groups according to their VO$_{2max}$ values. The groups are defined as: "not athlete" (49.15±8.44 mL.kg-1.min-1); "amateur" (58.69±5.68 mL.kg-1.min-1); and "elite" (69.13±4.97 mL.kg-1.min-1). All subjects have signed a consent form. These values were obtained from the study named Multifactorial Study of the Performance of Athletes in Street Racing Capixabas. The study was approved by the Research Ethics Committee from UFES, number 261.897, in May 06, 2013.

Procedures

For each subject, it was applied a questionnaire to collect personal and medical information, practices of exercise and training, and individual economical aspects.

The anthropometric evaluation includes determination of body mass, stature (balance and stadiometer from MARTE LTDA, model LC 200, 2009). Measures of skinfolds (adipometer Cescorf, Mitutoyo with precision of 0.1 mm). The fat percentage was obtained through the seven skinfolds protocol: subscapular, triceps, pectoral, mid axillary, suprailiac, abdominal and thigh. The calculation was performed by the Pollock protocol.[15]

For each subject, the cardiologist performed a resting electrocardiogram (ECG) and the cardiopulmonary exercise test (CPET).

The 1% inclination ramp protocol adapted from Bosch et al.[16] was used for the tests, with duration time estimated between 8 and 12 minutes. Subjects were instructed to interrupt the test under voluntary exhaustion. The temperature was maintained around 22°C through air conditioner, following the guidelines of the Brazilian Society of Cardiology[17].

The following variables were obtained on each breath through CPET: maximal ventilation (VE); oxygen uptake (VO$_2$); carbon dioxide production (VCO$_2$); respiratory exchange rate (RER); and

the oxygen and carbon dioxide equivalents (VE/VO$_2$ and VE/VCO$_2$, respectively). The Cortex Metalyzer 3B metabolic system (Leipzing, Germany) and the Inbra Sport treadmill (Super ATL model, Porto Alegre, Brazil) were used.

We considered the following possibilities for the VO$_2$ kinetics behaviour as function of the runner's speed:

B1.   In the absence of plateau, the VO$_2$ evolution as function of the speed can be divided in two stages. The first is characterized by a fast increase of VO$_2$, which consists of organism adaptation in the beginning of the test. The second delimits the linear progression of the VO$_2$;

B2.   In the presence of plateau, additionally to the two stages described in the above item, a third stage occurs, which is characterized by VO$_2$ stabilization (zero slope) when increasing the exercise load.

See in Figure 1 the illustration of these two behaviours.

If the change points between stages were known, the standard linear regression would be enough to fit the data. However, known breakpoints are not feasible in this experiment design. Many studies in literature[11-14] have adapted standard linear regression to circumvent this problem. In general, as previously discussed, these methodologies require parameter specification from the researcher. This high subjectivity degree may lead to different conclusions for the same data set. This motivates us to introduce a new objective method for identifying VO$_{2max}$ plateau, described next.

We suggest the following two-step strategy for VO$_{2max}$ plateau identification in ramp protocol:

Step 1 (Segmented Regression): In this step, segmented linear regression analysis with unknown breakpoints[18,19] is used to fit the data. Specifically, to the same subject, we consider estimation of two segmented models: Model (1), with two segments, denoting Stages 1 and 2, which represents the absence of a plateau, describing by Behavior B1 (see Figure 1(A)); and Model (2), with three segments and the slope of the third segment fixed as zero, which represents the presence of a plateau, describing by Behavior B2 (see Figure 1(B)).

Step 2 (Wald's Test): In this framework, deciding between non plateau versus plateau is equivalent to test the following statistical hypotheses: (null – non plateau) Models (1) and (2) provide similar fit versus (alternative – plateau) Model (2) provides better fit than Model (1). In order to statistically confront these models and decide between a non plateau versus a plateau, it was used the Wald test.[20] In this framework, a small *p*-value (*p*-value < 0.05,

in this paper) gives strong statistical evidence to reject the null hypothesis and to conclude that particular athlete has presented plateau in VO$_2$.

The two-step methodology discussed in this subsection was implemented in the R computational environment[21], using the packages "Segmented", "MASS" and "lmtest". The code can be provided by the authors upon request.

It is worth to point out that, when the athlete presents a plateau, Model (1) might not provide an adequate fit. Figure 2 illustrates this behaviour. Nevertheless, the proposed methodology still indicates that this athlete develops a plateau in VO$_2$.

On the other hand, although it did not happen in this study, if the athlete does not develop a plateau, this can cause a convergence problem in estimation of Model (2), since the second breakpoint would be close to the boundary of the applied speeds (covariate). Under divergence of the "segmented" package in estimation of Model (2), we suggest establishing a non plateau and *p*-value = 1.

Statistical analysis

We used the proposed methodology to classify the 41 subjects into two groups: those who performed VO$_{2max}$ plateau, the Plateau group; and those who did not develop the plateau, the Non-plateau group. These ensure an automatic (blinded) classification criterion, since it does not depend on researcher subjective specifications. The data were summarized in terms of sample mean and standard deviation. To compare anthropometric and fitness features between the groups, the two-sample t test was used. To test for equality of more than two proportions, the chi-squared test for contingency tables was employed.

Results

Before further analysis, the 41 subjects were objectively categorized into Plateau and Non-plateau groups by the proposed identification procedure. As illustration of this method, in Figure 3 is displayed the results of Model (1) and (2) fitted to Athletes 1 and 8 (Step 1), as well as the *p*-values from Wald's test to compare these models (Step 2). As can be seen, Athlete 1 did not present plateau (Figure 3A, *p*-value = 0.994), whilst Athlete 8 develops plateau (Figure 3B, *p*-value ≈ 0). Note that the proposed methodology was able to properly classify the absence and the presence of a plateau in VO$_2$ data.
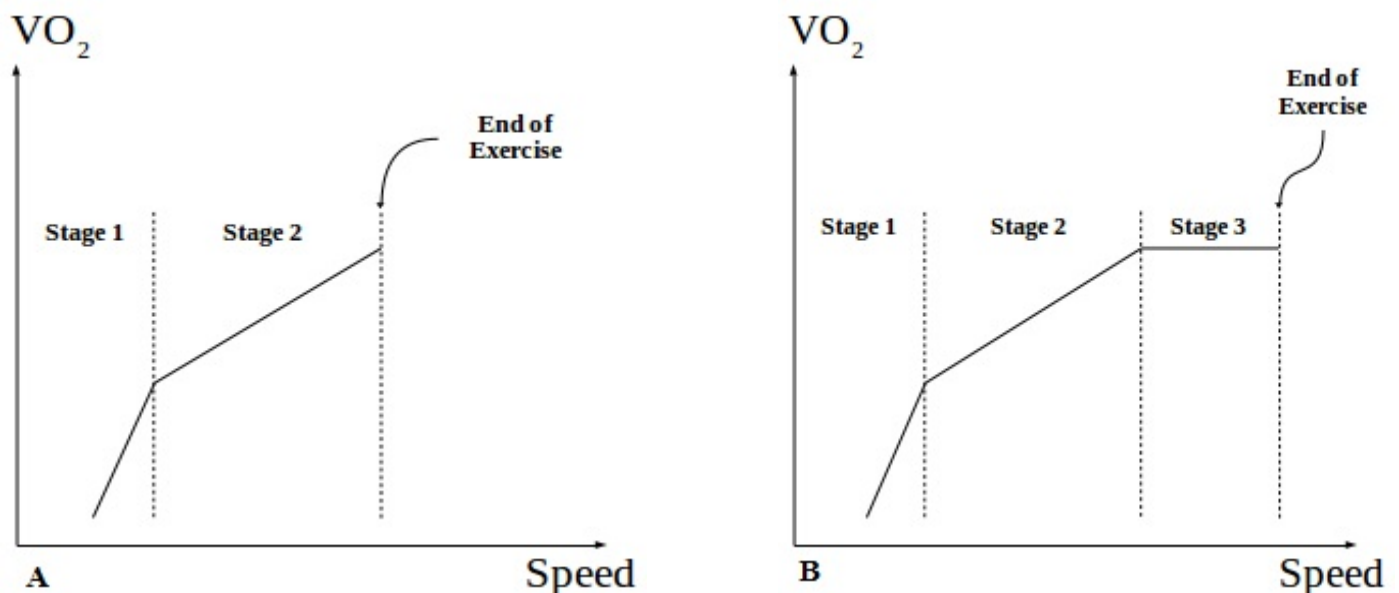

Figure 1. Expected behaviors of the VO$_2$ kinetic evolution as function of the runner's speed. (A) absence of plateau. (B) presence of plateau.
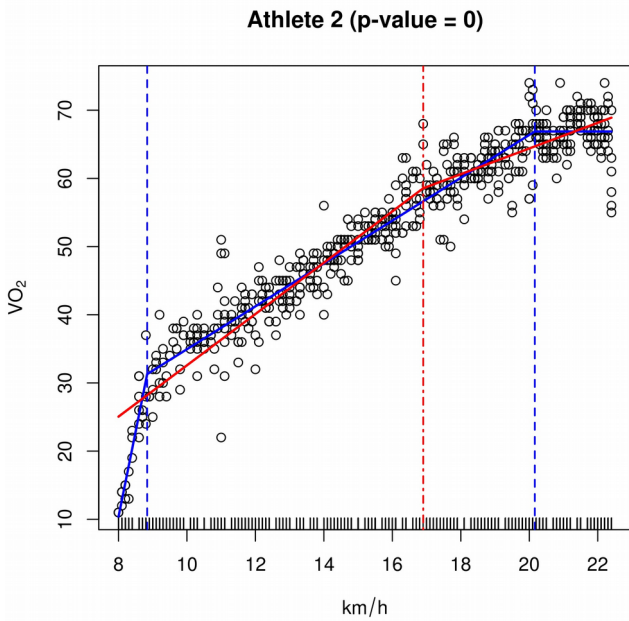
Figure 2. Illustration of misfitting of Model (1), in red lines, to the data.

Table 2. Metabolic, ventilatory and velocity variables.

Variable	Plateau (24)	Non-Plateau (17)	*p*-value
RER_{max}	1.13±0.04	1.13±0.10	0.807
HR_{max} (beats.min^{-1})	190.2±10.8	194.6±13.8	0.256
V_{max} (km.h^{-1})	19.0±2.9	18.6±2.4	0.630
Test Time (min)	11.24±1.26	11.27±1.27	0.932
VCO_2 VO_2max (L.min^{-1})	4.34±0.45	4.12±0.62	0.210
VEmax VO_2max	135.57±21.08	124.42±21.82	0.108
VO_2max (mL.kg^{-1}.min^{-1})	56.62±11.52	55.88±9.09	0.826
VO_2max (L.min^{-1})	4.06±0.44	3.84±0.47	0.151
VO_2/HR VO_2max	21.84±2.69	20.10±3.07	0.062
V_{LA} (km.h^{-1})	13.1±1.4	11.8±3.0	0.228

RERmax: Respiratory Exchange Ratio; HRmax: Maximal Heart rate; Vmax: Maximal speed; VCO₂: Carbon dioxide output; VEmax: Maximal ventilation; VO₂max: Maximum oxygen consumption; VO₂/HR: Oxygen Pulse; VLA: Speed at the anaerobic threshold; Values presented as mean ± SD; *p*-value for the t-Student test for independent samples.

Table 3 presents the plateau incidence by individual profile. According to the high *p*-value, there is no evidence of different proportions. The sample size (N=41) may be small to give reliable conclusions, considering that this test is only asymptotic (for large N). Although the incidence differences related to the profile are not significant, in a descriptive level, it indicates that, the higher the level of professionalism, the greater the chance of the individual developing the plateau.

Table 1 presents the comparison of anthropometric characteristics between the individuals of Plateau (P) and Non-plateau (NP) groups. There was no significant difference, suggesting similarity between them in all characteristics evaluated.

Table 3. Incidence of plateau by athlete profile.

Profile	Plateau incidence
Not athlete	52.38% (11/21)
Amateur	63.64% (7/11)
Elite	66.67% (6/9)
p-value	0.708

p-value of chi-square test for equality between the plateau proportions in different profiles.

Table 1. Anthropometric and age characterization of the sample.

Characteristics	Plateau (24)	Non-plateau (17)	*p*-value
Weight (kg)	73.42±13.41	69.82±10.02	0.356
Height (cm)	176.04±7.18	172.67±7.38	0.151
Age (Years)	33.04±5.37	30.82±5.70	0.212
Fat (%)	13.1±6.66	12.27±3.10	0.635

Values presented as mean ± SD; Skinfolds evaluated: tricipital, subscapular, mid axillary, pectoral, suprailiac, abdominal and thigh; *p*-value for the t-student test for independent samples.

Table 2 presents the same analysis of Table 2 for metabolic, ventilatory and velocity variables. Similarly, there was no statistical difference for any of the variables.

Discussion

This study proposed and applied a new methodology for VO_{2max} plateau identification, applicable to the ramp protocol and individualized to each subject. The literature review suggested that future studies should investigate the validity and reliability of a VO_2 plateau criterion based on the VO_2/charge ratio[2] individual slope. The proposed model follows this premise and analyses the whole data, with no need to be pre-established by the researcher a final period of the test, nor a slope threshold or consecutive differences, to verify the stabilization of VO_2. This naturally introduces objectivity to the identification procedure, since it is completely data-driven.
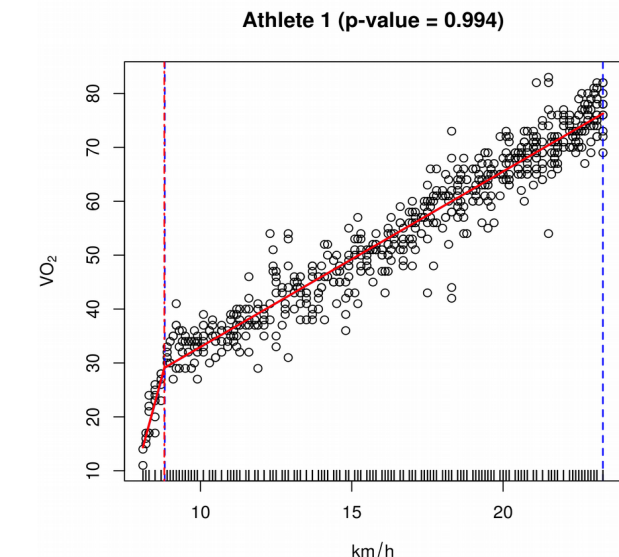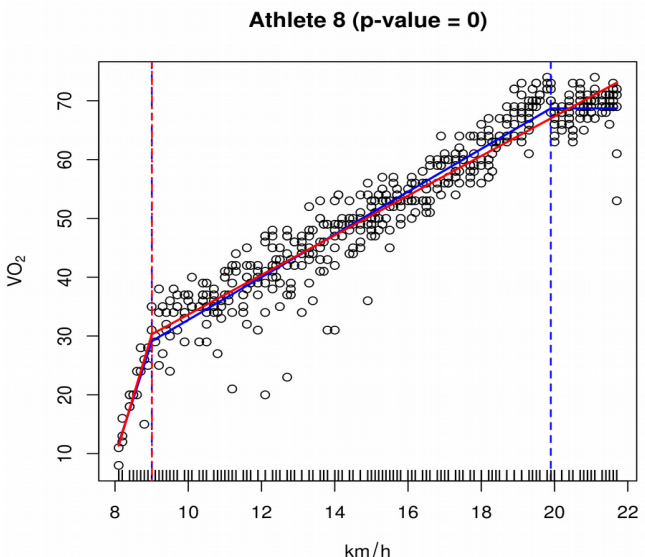
A **B**

Figure 3. Illustration of the proposed methodology. Displays VO₂ as function of the runner's speed (km/h). Red and blue lines represent the fitted values from Models (1) and (2), respectively. (A) Absence of a plateau, with p-value = 0.994. (B) Presence of plateau, with p-value ≈ 0.

Studies have reported that the traditional plateau analysis, considering a ΔVO$_2$ cut within pre-established stages, may be inadequate to the ramp protocol.[12] With this, some authors have reported low percentages of occurrence of the plateau.[1,12] However, some studies contradict these findings, with high percentages of plateau occurrence,[8,13] demonstrating that, there is no consensus in the literature yet.

As showed here, no statistical difference was found between the individual characteristics, according to the occurrence of the plateau. Demonstrating a similarity between the groups.

For metabolic, ventilatory and velocity variables, no statistically significant differences were found when comparing groups with and without plateau. Lucia et al.[22] have worked with a similar sample and obtained a percentage for the plateau of 47%. The authors also analyzed variables such as: VO$_{2max}$, RTR$_{max}$ and HR$_{max}$ and corroborating for the results in this study, also no significant differences were found between the groups with and without plateau. That research have reported that individuals who reached plateau presented higher concentration of lactate and lower pH levels when compared to those who did not reach plateau. Unfortunately, this is a limitation of this study since these variables were not analyzed. Studies have suggested that lactate concentration may indicate a greater anaerobic adaptation of the subject when, even with higher exhaustion levels, the subject is still able to sustain load increases without increasing VO$_2$ for a period.[14] Corroborating to this point of view, Gordon et al.[23] concluded that there was an inverse correlation between ΔVO$_2$ and the maximum accumulated oxygen deficit (r=-0.77, *p*-value=0.008), suggesting that plateau occurrence is dependent on anaerobic metabolism and that the wide range of plateau occurrence found in literature may be consequence of the variety of subjects anaerobic capacity. Refuting these findings, Silva et al.[24], with young male athletes, have shown that the anaerobic capacity is not a decisive factor for VO$_{2max}$ determination, finding a non-significant inverse correlation between ΔVO$_2$ and the accumulated maximum oxygen deficit (r = -0.61, *p*-value = 0.270). On the other hand, these results were obtained from a sample of physically active individuals and not from highly trained athletes, as presented by Gordon et al.[23]. With this, it can be assumed that there are other variables that may interfere with the occurrence or not of the VO$_{2max}$ plateau.

In this way, it is possible that individuals who did not reach plateau had low blood lactate levels or presented some relation between ΔVO$_2$ and maximum accumulated oxygen deficit. However, as previously mentioned, these variables were not measured here. In this same view, Wagner et al.[25] proposed that some subjects do not achieve plateau due to unpleasant symptoms caused by exhaustion, such as dyspnea and/or leg pain. Therefore, another possible justification for the subjects that did not show plateau, is a possible lack of motivation/effort. However, all stimuli were given by the test applicator to ensure a maximum stress test. On the other hand, studies show that even tests applied in elite athletes have revealed low percentages of plateau occurrence.

With the application of this methodology was found a percentage of 58.54% of occurrence of the plateau, being this result within the values found in the literature. Regarding the characteristics of aptitude, no statistically significant differences were found between the group with and without plateau, demonstrating that, for the variables analyzed, these two groups are not different. Some studies have been devoted to studying the reasons why some individuals reach the plateau in relation to others, however these reasons are still not clear in the literature. In view of the above, more research is needed to test the validity and reproducibility of the proposed method, as well as to clarify the factors involved in the realization or not of the VO$_{2max}$ plateau.

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