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Title page

Title of article: Validity of oxygen uptake cut-off criteria in plateau identification during horizontal treadmill running

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Abstract

BACKGROUND: When determining achievement of maximal oxygen uptake ($\dot{V}O_{2max}$) during treadmill running using speed increments, the $\dot{V}O_2$ cut-off criteria applied during plateau identification is often not justified, not protocol specific, or not related to actual change in $\dot{V}O_2$ ($\Delta\dot{V}O_2$) with speed increment, which can influence plateau achievement rates between studies. The purpose of this study was to compare plateau incidence using an individualised plateau criteria approach based on a ‘percentage’ $\Delta\dot{V}O_2$ compared to using previously established criteria of $\Delta\dot{V}O_2 \leq 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ not developed on running speed.

METHODS: Fifty-four males completed a ramp horizontal treadmill test with 0.5 or 1.0 $\text{km}\cdot\text{h}^{-1}$ per minute ($\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$) speed increments to measure $\dot{V}O_{2max}$. Average $\Delta\dot{V}O_2$ for the each 1-minute speed increment was determined and used to develop individualised cut-off criteria deemed to be a plateau: a final $\Delta\dot{V}O_2$ of less than 50% of the average change elicited between consecutive speed increments during the test ($\dot{V}O_2 \leq 50\%$); plateau incidence using this was compared to $\Delta\dot{V}O_2 \leq 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($\dot{V}O_2 \leq 2.1$).

RESULTS: Mean $\Delta\dot{V}O_2$ was 1.74 ± 0.59 and $3.09 \pm 0.59 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for 0.5 and 1.0 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ increments respectively. $\dot{V}O_2$ cut-off criteria were met by 48%/65% (1.0 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$) ($P=0.234$) and 53%/100% (0.5 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$) ($P=0.003$) for $\dot{V}O_2 \leq 50\%$ and $\dot{V}O_2 \leq 2.1$ respectively.

CONCLUSIONS: Use of $\dot{V}O_2 \leq 2.1$ resulted in distortedly high plateau achievement, particularly for smaller speed increments where the $\dot{V}O_2$ -speed relationship was actually less than $\dot{V}O_2 \leq 2.1$ making its use inappropriate. Use of $\dot{V}O_2 \leq 50\%$ may be a suitable alternative, but as a plateau was not consistently demonstrated, application of cut-off criteria should not be a requirement in deciding whether one’s achieved $\dot{V}O_{2max}$.

Key words: $\dot{V}O_2$ -speed relationship, $\dot{V}O_2$ plateau, $\dot{V}O_2$ cut-off criteria, horizontal treadmill running

Introduction

During assessment of maximal oxygen uptake ($\dot{V}O_{2\max}$), the use of a primary criterion (plateau in oxygen uptake ($\dot{V}O_2$)) to determine achievement of $\dot{V}O_{2\max}$ is widely used during assessment of cardiorespiratory fitness.¹ A $\dot{V}O_2$ plateau can be described as a “true plateau” when no further increase in $\dot{V}O_2$ occurs despite further increases in work rate (WR).¹ It can also be described as a “levelling-off” when the increase in $\dot{V}O_2$ occurs at a reduced rate as WR becomes more intense in the final stages of a graded exercise test. However, the latter is more difficult to visually observe and because large variation exists in its definition, what constitutes a ‘levelling-off’ plateau differs amongst studies, with different $\dot{V}O_2$ cut-off values used to determine if $\dot{V}O_{2\max}$ is attained. For example, some cut-off values are considered more stringent, whilst others are more attainable, ranging from a change in $\dot{V}O_2$ ($\Delta\dot{V}O_2$) of $\leq 50 \text{ ml}\cdot\text{min}^{-1}$,²⁻⁵ $\leq 1.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$,⁶⁻⁷ $\leq 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, $150 \text{ ml}\cdot\text{min}^{-1}$ or within 2 standard deviations (2-SD) of the expected rise in $\dot{V}O_2$,⁸⁻¹¹ and a $\Delta\dot{V}O_2$ of less than 50% of the average change elicited between consecutive test stages.¹²⁻¹⁴ Rationale for application of specific cut-off criteria is not always apparent. The varying magnitude of cut-off criteria may influence the frequency of plateau achievement, which is highly variable in adults across studies for treadmill running and cycle ergometry, ranging from as low as 24%-33%,¹² 25-39%,⁶ 47%,⁷ and 50%-60%⁹⁻¹⁰ to higher incidences such as 62%¹⁴ and 60-80%,³ and some studies showing a wide range of achievement from 20-80%⁸ and 8-57%.⁴

Whilst a number of studies have evaluated plateau incidence for cycle ergometry^{2 5 7 14-15} and uphill treadmill running,^{3 4 6 8 10-13} work evaluating plateau incidence for horizontal treadmill running is sparse. Furthermore, those that have^{8 10} applied extensively used plateau criterion developed by Taylor *et al.*¹¹ to confirm plateau achievement, even though it was developed

on increments in treadmill gradient rather than running speed and used a discontinuous rather than continuous protocol. In brief, Taylor *et al.*¹¹ found the mean rise in $\dot{V}O_2$ for 2.5% increments in gradient at 7mph every 3 minutes was $299.3 \pm 86.5 \text{ ml}\cdot\text{min}^{-1}$ or $4.18 \pm 1.07 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (range 159-470 $\text{ml}\cdot\text{min}^{-1}$ or 2.2-5.9 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). From this, they deduced that $\dot{V}O_{2\text{max}}$ was achieved when the change in $\dot{V}O_2$ was within 2-SD of the expected rise [$\leq 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ or $\leq 150 \text{ ml}\cdot\text{min}^{-1}$ for a 72kg person] on different testing days. In this case, the expected rise in $\dot{V}O_2$ was based on the $\dot{V}O_2$ -WR relationship for a specific exercise protocol; a cut-off of $2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, which is considered generous,¹ is cited in the methodology of numerous papers as the cut-off criteria, yet it cannot simply be universally applied to all test termination scenarios. Instead, any cut-off criteria applied should be related to the actual change in $\dot{V}O_2$ with exercise stage for each specific protocol. Such criteria have been developed for inclined running¹²⁻¹³ and cycle ergometry,¹⁴ using a final change in $\dot{V}O_2$ of less than 50% of the average change elicited between consecutive stages during the test to identify achievement of $\dot{V}O_{2\text{max}}$. However, this approach has not yet been used for horizontal treadmill running using speed increments and requires knowledge of $\dot{V}O_2$ -speed relationship. Although ramp protocols that increase treadmill gradient instead of speed have been shown to be more successful at achieving $\dot{V}O_2$ plateau and a higher $\dot{V}O_{2\text{max}}$,^{8 10 16-17} a protocol using speed increments is arguably more useful for those who predominantly train on level surfaces, which allows determination of velocity at $\dot{V}O_{2\text{max}}$ subsequently used to prescribe training speeds.¹⁸

The purpose of this study was to determine the average change in $\dot{V}O_2$ for speed increments of 0.5 and 1.0 km·h⁻¹ every minute during horizontal treadmill running in order to develop an individualised plateau criteria approach where a final change in $\dot{V}O_2$ of less than 50% of the average change elicited between consecutive speed increments during the test would be deemed a plateau. Application of this plateau criteria will be compared to use of ‘previously established’ and commonly applied cut-off criteria of Taylor *et al.*¹¹ of $\Delta\dot{V}O_2 \leq 2.1$ ml·kg⁻¹·min⁻¹ not developed on speed increments. Plateau incidence will be evaluated and the validity of their application will be considered.

Materials and methods

Participants

The experimental protocol was submitted to and approved by the Faculty Ethics Committee following the principles outlined in the Declaration of Helsinki. Participants that responded to a recruitment poster were provided with detailed verbal and written explanation of the aims, procedures, and any risks involved in the investigation, and completed a health history questionnaire including details on training activity levels prior to participation. Eligible participants then provided written informed consent.

Fifty-four moderately well-trained males (mean \pm SD: Age 22.70 \pm 3.60 years, height 178.44 \pm 7.03 cm, body mass 76.23 \pm 10.58 kg; $\dot{V}O_{2\max}$ 53.30 \pm 5.69 ml·kg⁻¹·min⁻¹ (range 42.30 – 65.93 ml·kg⁻¹·min⁻¹)) with a recreational-competitive training background in either football or distance running participated in the study. Before the testing sessions, participants were advised about the importance of maintaining their normal nutritional intake, particularly

carbohydrate consumption, and to remain well hydrated. Participants were asked to avoid eating food for 2 hours prior to testing, to avoid caffeine on the day of testing, and to avoid heavy exercise or excess alcohol consumption for 24 hours prior to participation.

Experimental design

Maximal exercise testing

The participants reported to the laboratory for testing on two occasions, for familiarisation and for maximal exercise testing. All participants performed horizontal treadmill running to exhaustion on a motorised treadmill (Woodway Ergo ELG55, Weil am Rhein, Germany) using a graded continuous ramp protocol with speed increments of either 0.5 km·h⁻¹ (n= 23) or 1.0 km·h⁻¹ per minute (km·h⁻¹·min⁻¹) (n = 31), starting at 9 km·h⁻¹. A standardised warm-up and cool-down was performed prior to and after the test. Expired gas was measured and analysed continuously using a Metalyzer 3B online gas analyser (Cortex, Biophysik GmbH, Leipzig, Germany) interfaced with a data acquisition system following calibration for gas concentrations using standard reference gases and for gas volume using a 3-litre gas syringe (Hans Rudolph). Heart rate (HR) was measured using a heart rate monitor (Polar Sport Tester, Polar Electro, Kempele, Finland) to observe physical exertion. All tests lasted no more than 8-12 minutes⁵ for 1.0 km·h⁻¹·min⁻¹ or 8-17 minutes²³ for 0.5 km·h⁻¹·min⁻¹ increments. The test was terminated when the participant reached volitional exhaustion, could not keep pace with treadmill, or was unable to continue despite vigorous encouragement. Data averaging of breath-by-breath data was performed after data collection using 30-second averages.^{14 24} Peak $\dot{V}O_2$ obtained during the treadmill test was taken as $\dot{V}O_{2max}$.

Identification of $\dot{V}O_2$ -speed relationship and $\dot{V}O_2$ plateau

In order to identify the pattern of $\dot{V}O_2$ response to the incremental exercise test, $\dot{V}O_2$ values were plotted as a function of the corresponding speed to obtain $\dot{V}O_2$ -speed relationship for each participant, and these were then interpolated by least squares linear regression, the slope of which yielded the average rise in $\dot{V}O_2$ ($\text{ml}\cdot\text{min}^{-1}$ and $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) between consecutive treadmill speeds for 0.5 and 1.0 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ speed increments.²⁵ Linear regression was firstly applied through the portion of the curve where the relationship between $\dot{V}O_2$ and running speed showed linearity (example - figure 1), and further applied to the portion of the slope as it levelled off (deceleration of the $\dot{V}O_2$ response) in the final stage or stages to determine incidence of $\dot{V}O_2$ plateau. Achievement of $\dot{V}O_2$ plateau was considered to have occurred when either a 'true' plateau was demonstrated (no change in $\dot{V}O_2$ -speed slope, or fall in $\dot{V}O_2$ with further speed increments), or if a 'levelling' plateau was achieved using the following $\dot{V}O_2$ cut-off criteria: a final change in $\dot{V}O_2$ of less than 50% of the average change in $\dot{V}O_2$ elicited between consecutive treadmill speeds during the test for each participant (e.g. ≤ 1.5 out of $3.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) ($\dot{V}O_2 \leq 50\%$),¹²⁻¹⁴ or a rise in $\dot{V}O_2 \leq 2.1 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ ($\dot{V}O_2 \leq 2.1$)¹¹ (figure 2).

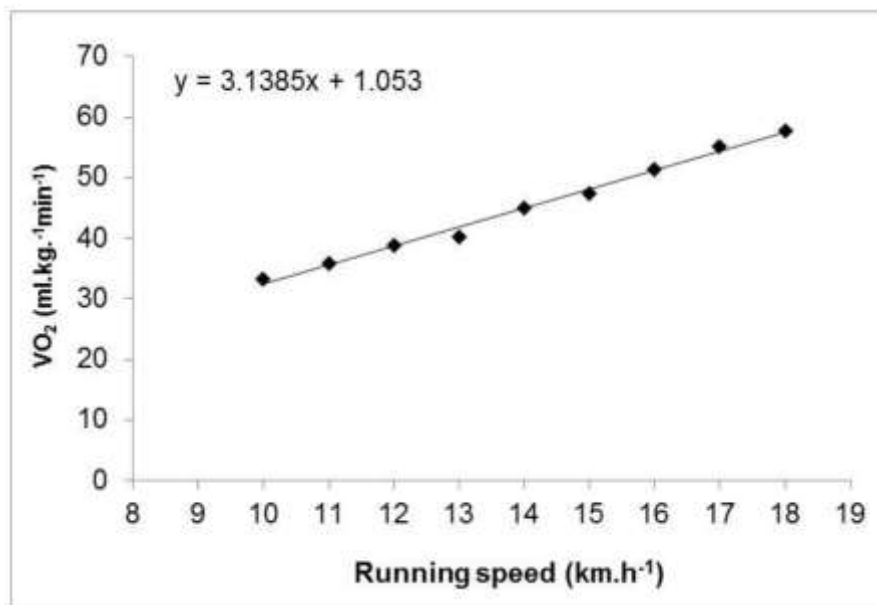


Figure 1: use of linear regression to determine the $\dot{V}O_2$ -running speed relationship for one participant for a range of running speeds of 10-18 km.h⁻¹.min⁻¹.

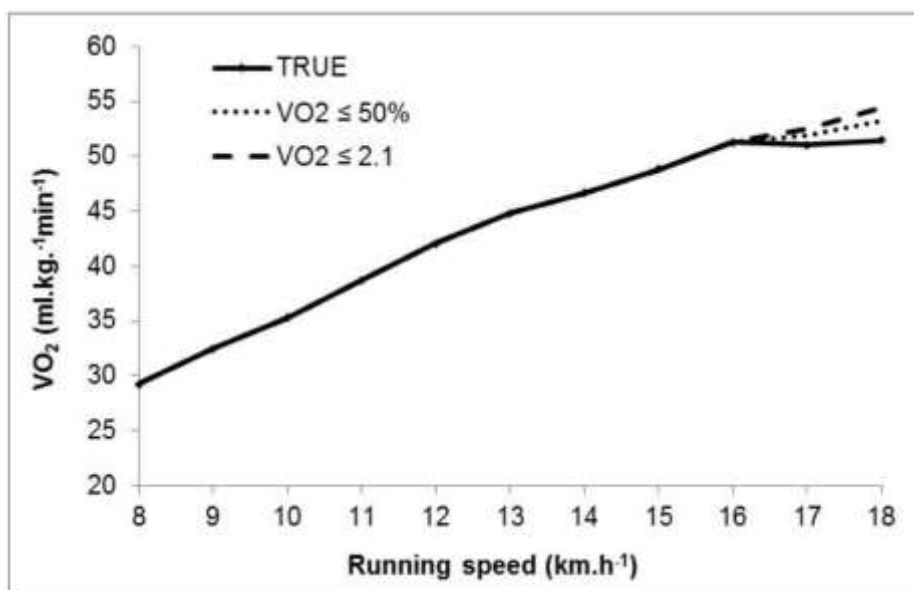


Figure 2: example of $\dot{V}O_2$ -running speed relationship for one participant with demonstration of the two 'levelling' cut-off criteria in the final stages of the test, and 'true' plateau.

Statistical analyses

Analysis was performed with the Statistical Package for Social Sciences (SPSS), version 23. The slope of the $\dot{V}O_2$ -speed relation for each ramp test was determined using linear regression. The $\dot{V}O_2$ data are presented as mean \pm SD and range (minimum-maximum). The frequency of plateau occurrence with respect to the number of participants satisfying each $\dot{V}O_2$ cut-off criteria is expressed as a percentage (%). A Chi-square and Fisher's exact test were used to explore the relationship between the independent variable (cut-off criteria) and the dependent variable (% achievement of plateau) for both speed increment protocols.

Results

The mean rise in $\dot{V}O_2$ for running speed increments of 0.5 and 1.0 km·h⁻¹·min⁻¹ during horizontal treadmill running was 1.74 ± 0.21 and 3.09 ± 0.59 ml·kg⁻¹·min⁻¹ (135.09 ± 27.02 and 222.82 ± 36.30 ml·min⁻¹) respectively, with a notable range amongst participants for both speed increments as reported in Table I. Achievement of $\dot{V}O_2$ cut-off criteria ranged from 48-100% (Figure 3) depending on criteria applied. Of the 31 participants from the 1.0 km·h⁻¹·min⁻¹ protocol, 8 (26%) achieved a true plateau, and of the remaining 23 participants, 15/23 and 11/23 achieved plateau criteria for $\dot{V}O_2 \leq 2.1$ and $\dot{V}O_2 \leq 50\%$ respectively with no significant difference (P=0.234). Of the 23 participants from the 0.5 km·h⁻¹·min⁻¹ protocol, 6 (also 26%) achieved a true plateau, and of the remaining 17 participants, Fisher's exact test found a significant difference (P =0.003, phi = 0.555) between the 17/17 and 9/17 that achieved $\dot{V}O_2$ cut-off criteria for $\dot{V}O_2 \leq 2.1$ and $\dot{V}O_2 \leq 50\%$ respectively.

TABLE I: Mean \pm SD change in absolute ($\text{ml}\cdot\text{min}^{-1}$) and relative ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) $\dot{V}\text{O}_2$ with increase in running speed of 0.5 and 1.0 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$; range of $\dot{V}\text{O}_2$ change also shown.

| Change in running speed | Absolute change in $\dot{V}\text{O}_2$ ($\text{ml}\cdot\text{min}^{-1}$) | Relative change in $\dot{V}\text{O}_2$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) |
|---|--|---|
| 0.5 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ | 135.09 \pm 27.02 Range 101-201 | 1.74 \pm 0.21 Range 1.28-2.09 |
| 1.0 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ | 222.82 \pm 36.30 Range 170-300 | 3.09 \pm 0.59 Range 2.37-4.76 |

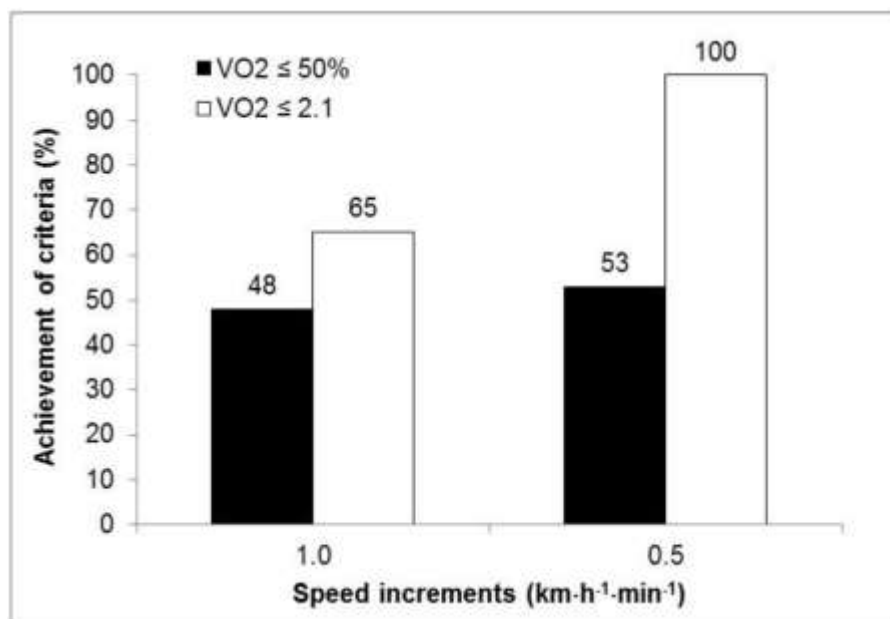


Figure 3: Percentage of participants achieving a $\dot{V}\text{O}_2$ plateau for the two speed increment protocols for the cut-off criteria applied including a rise in $\dot{V}\text{O}_2$ within 50% of the observed rise in $\dot{V}\text{O}_2$ ($\Delta\dot{V}\text{O}_2 \leq 50\%$) and within 2.1 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($\Delta\dot{V}\text{O}_2 \leq 2.1$)

Discussion

In brief, this study evaluated the frequency of $\dot{V}\text{O}_2$ plateau criteria achievement during horizontal treadmill running using cut-off criteria based on the ‘actual’ change in $\dot{V}\text{O}_2$ using a final rise in $\dot{V}\text{O}_2$ of less than 50% of the average change in $\dot{V}\text{O}_2$ elicited across running

speeds for each participant ($\dot{V}O_2 \leq 50\%$) compared to use of previously established cut-off values not developed on increments in running speed ($\dot{V}O_2 \leq 2.1$) in order to ascertain which, if any, cut-off criteria may be recommended when determining attainment of $\dot{V}O_{2max}$. The current study demonstrates that plateau occurrence is variable depending on the cut-off criteria applied, with the criteria of Taylor *et al.*¹¹ ($\dot{V}O_2 \leq 2.1$) yielding the highest plateau achievement rates compared to $\dot{V}O_2 \leq 50\%$. This is not particularly surprising, as the extensively used criterion of Taylor *et al.*¹¹ is often considered generous and more attainable when applied to other protocols.¹ Based on the average $\dot{V}O_2$ -speed relationship reported here for $1.0 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ ($3.09 \pm 0.59 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), it is apparent that the $\dot{V}O_2 \leq 2.1$ cut-off is more generous than a $\dot{V}O_2 \leq 50\%$ (equivalent to an average of $1.55 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for $1.0 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$). Furthermore, the average $\dot{V}O_2$ -speed relationship for $0.5 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ increments of $1.74 \pm 0.21 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ was actually 'lower' than the $2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ cut-off criteria of Taylor *et al.*;¹¹ all participants using this protocol demonstrated a $\dot{V}O_2$ -speed relationship of less than $2.1 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$, and so by definition, all technically met this criterion, even though $\dot{V}O_2$ slowing did not necessarily occur. Hence, plateau criteria that exceeds the $\dot{V}O_2$ -speed relationship clearly cannot and should not be applied.

Nevertheless, the few studies^{8 10} that have evaluated plateau incidence for horizontal treadmill running have both applied criterion of Taylor *et al.*¹¹ St Clair Gibson *et al.*¹⁰ reported 50% plateau achievement, lower than the 65% observed in the current study. Unfortunately, their 50% achievement was based on those reaching a plateau in either an incline protocol or horizontal speed protocol ($1 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$), but plateau incidence for the speed protocol alone was not reported making any direct comparison not feasible. In contrast, Draper *et al.*⁸ demonstrated only 20% achievement rate using a horizontal speed ramped protocol despite

their use of larger speed increments ($1.2 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$); their development of protocol specific criteria using the ‘approach’ of Taylor *et al.*¹¹ to identify occurrence of $\dot{V}\text{O}_2$ plateau (e.g. plateau incidence identified using $\Delta\dot{V}\text{O}_2 \leq$ two standard deviations of the rise in $\dot{V}\text{O}_2$ instead of $\Delta\dot{V}\text{O}_2$ of $\leq 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) could explain their lower plateau achievement rate. Alternatively, the low plateau incidence may have been influenced by their use of 60-s averages, which can result in lower plateau incidence compared to shorter sampling intervals.²

With respect to the plateau criteria using $\dot{V}\text{O}_2 \leq 50\%$, there is no comparative data for horizontal treadmill running, but it has been applied during cycle ergometry¹⁴ and uphill running.¹²⁻¹³ Poole *et al.*¹⁴ reported plateau achievement of 62.5% using $20 \text{ W}\cdot\text{min}^{-1}$ increments, higher than the 48-53% reported in the current study. In contrast, Brown *et al.*¹² found lower plateau incidence of 23.8% and 33.3% for 2.5% increase in treadmill gradient every 2-mins in men whilst running at 8.04 or $11.26 \text{ km}\cdot\text{h}^{-1}$ respectively, and Draper *et al.*¹³ reported plateau achievement of 40% for the same gradient increments every 1-min at $8.04 \text{ km}\cdot\text{h}^{-1}$ in boys. Although protocols using gradient rather than speed increments have been shown to be more successful at achieving $\dot{V}\text{O}_2$ plateau^{8 10 17} the lower plateau incidence¹²⁻¹³ may be attributable to their use of 60-s averages compared to 30-s used by Poole *et al.*¹⁴ and the current study – a sampling frequency reported to offer high precision and reasonable sample intervals for incremental testing.²⁴ Using cut-off criteria that equates to a percentage of the actual $\dot{V}\text{O}_2$ -speed relationship may offer a consistent and simple approach, and may be better than applying absolute cut-off values with no clear rationale for their choice.

Moreover, when one considers factors that can influence the $\dot{V}\text{O}_2$ -speed relationship for WR increments during an exercise test, it is difficult to justify the use of previously established

cut-off values. The rise in $\dot{V}O_2$ per increment can be influenced by stage duration and size of WR increment. These factors can affect the $\dot{V}O_2$ response for which there are three phases during transition from rest to constant-load exercise: a very early rapid cardiodynamic phase (phase I), the primary/fast component (phase II) and the secondary/slow component (phase III) where $\dot{V}O_2$ increases more slowly or plateaus.²⁶ Hence, the expected rise in $\dot{V}O_2$ per exercise stage will be influenced by how much all three phases contribute to the overall $\dot{V}O_2$ response. A smaller rise in $\dot{V}O_2$ would be expected for ramp exercise protocols using 60-s stages frequently used in assessing $\dot{V}O_{2max}$ compared to protocols that use longer stage lengths of 3-min that may have a greater contribution from the slow component.²⁷⁻²⁸

With respect to the magnitude of the WR increment, the bigger the increment the higher the expected rise in $\dot{V}O_2$. For example, one would expect a rise in $\dot{V}O_2$ of approximately 200 ml·min⁻¹ for a 20 W·min⁻¹ and 300 ml·min⁻¹ for a 30 W·min⁻¹ increase in WR given that a $\dot{V}O_2$ increase of approximately 10 ml·min⁻¹·W⁻¹²⁶ and 9-11 ml·min⁻¹·W⁻¹²⁹ were reported for cycle ergometry. For inclined running, a rise in $\dot{V}O_2$ of approximately 2 ml·kg⁻¹·min⁻¹ was observed for 1% gradient increments each minute at running speeds exceeding 16 km·h⁻¹⁶ to double that at 3.9-4.18 ml·kg⁻¹·min⁻¹ for 2.5% gradient increments every 3-mins at 7mph.^{9 11} The average estimated rise in $\dot{V}O_2$ for increases in horizontal treadmill running speeds (range 8-20 km·h⁻¹) based on regression equation developed by Léger and Mercier²¹ were 1.58 ml·kg⁻¹·min⁻¹ for 0.5 km·h⁻¹ and 3.16 ml·kg⁻¹·min⁻¹ for 1 km·h⁻¹ increments, with wide variation at any speed amongst participants. This concurred with the current study – 1.74 ml·kg⁻¹·min⁻¹ and 3.09 ml·kg⁻¹·min⁻¹ for 0.5 and 1 km·h⁻¹ increments respectively. The oxygen cost of these speed increments were slightly higher than those reported by di Prampero *et al.*²⁵ and Carter *et al.*,²⁷ but slightly lower than values deduced from regression

equation developed by Jones & Doust²⁰ for horizontal treadmill running. These observed differences in the $\dot{V}O_2$ rise with intensity could be a function of the protocols used or differences in participant demographics between studies.

The notable range (table 1) and large individual variability in $\dot{V}O_2$ -speed relationship between participants appears to support this, and may be related to training status,^{19 21 30} muscle fibre type,³¹⁻³² gender,³³ age,³⁴ physical inactivity or disease,³⁵ running technique and body mass. A key point here is the wide variability in the $\dot{V}O_2$ -speed relationship amongst participants is not conducive to applying standard plateau criteria such as $\dot{V}O_2 \leq 2.1$ ²⁴ and for many runners may be inappropriate. Although $\dot{V}O_2 \leq 50\%$ criterion appears to be a better approach, still only half of participants achieved it, again questioning the validity of applying plateau criteria at all. Supporting this, Day *et al.*¹⁵ concluded that a $\dot{V}O_2$ plateau was not consistently demonstrated during rapid incremental ramp protocols, with 83% of 71 participants showing $\dot{V}O_2$ continuing to increase linearly or an acceleration in $\dot{V}O_2$ during the last few minutes of the maximal exercise. Lucia *et al.*,⁷ Doherty *et al.*⁶ and Rossiter *et al.*³⁶ also concluded that, in endurance athletes, $\dot{V}O_2$ does not necessarily level off near to, or at, exhaustion. Hence, because $\dot{V}O_2$ plateau has not always been shown to be a reliable or universal marker of maximal effort, this questions the applicability of any $\dot{V}O_2$ cut-off criteria in determining achievement of $\dot{V}O_{2max}$ during ramp treadmill protocols.

In the absence of a plateau, secondary criteria have been frequently used to indicate achievement of $\dot{V}O_{2max}$.⁹ However, there are limitations around their use¹ and have been rejected as a valid means of verifying $\dot{V}O_{2max}$ in continuous ramp exercise test protocols¹⁴ – a discussion beyond the scope of this paper. If in doubt about the peak $\dot{V}O_2$ achieved during the maximal test, reliability could be evaluated by using a supra-maximal verification stage

following the $\dot{V}O_{2\max}$ test. Rossiter *et al.*³⁶ found no significant difference ($P=0.49$) in peak $\dot{V}O_2$ following a verification stage for cycle ergometer exercise. Verification stages using treadmill running have more commonly used inclined running at a constant running speed. For example, Foster *et al.*³⁷ and Mier, *et al.*³⁸ found no significant difference ($P>0.05$) in peak $\dot{V}O_2$ following a supra-maximal treadmill running verification stage. Kirkeberg *et al.*,³⁹ on the other hand, used a submaximal but longer inclined verification stage (at least 2-mins) and also found no significant difference ($P=0.19$) in peak $\dot{V}O_2$. Few studies have used a horizontal running verification stage, perhaps due to treadmill speed limitations or high leg speed requirements. However, Midgley *et al.*¹⁸ used a horizontal verification stage of 0.5 $\text{km}\cdot\text{h}^{-1}$ higher than achieved during $\dot{V}O_{2\max}$ and concluded that a verification stage is more robust than plateau criteria in confirming achievement of $\dot{V}O_{2\max}$.

Conclusions

In conclusion, based on the results of this study, plateau incidence is greatly influenced by the $\dot{V}O_2$ cut-off criteria applied. The widely applied plateau criterion of $\dot{V}O_2 \leq 2.1$ is too generous and not appropriate for ramp treadmill protocols using speed increments, particularly those using smaller speed increments where the average rise in $\dot{V}O_2$ per exercise stage is actually less than the cut-off criteria applied. If cut-off criteria are applied, they should be protocol specific based on the observed $\dot{V}O_2$ -speed relationship - $\dot{V}O_2 \leq 50\%$ could be a suitable alternative. However, because so many individuals do not demonstrate a plateau, application of cut-off criteria should not be a requirement in deciding whether one has achieved $\dot{V}O_{2\max}$ or not. A verification stage could be used as a more robust alternative to check reliability of the $\dot{V}O_{2\max}$ value, although careful consideration of protocol is required when using horizontal treadmill running at high running speeds.

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