Trained Runners Need Lower Respiratory Exchange Ratio Criterion During Graded Exercise Tests

Original Research

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Abstract

Introduction: A respiratory exchange ratio peak (RER_{peak}) of ≥1.10 is widely utilized as a secondary confirmation marker that *maximal effort* was achieved and a valid graded exercise tests (GXT) was conducted. However, this threshold may not be appropriate for trained runners. This study characterized National Collegiate Athletics Association Division I (*n*=30; female=14) cross-country runners' ability to reach the ≥1.10 criterion with respect to both sex and sampling interval (SI) duration.

Methods: Unfiltered RER_{peak} were determined during the last two minutes of a GXT in sampling intervals of 15-, 30-, and 60-s with strong vocal encouragement.

Results: There were no differences between sexes regardless of SI, but whole cohort RER_{peak} values were statistically significant ($p < 0.05$) among all SI (mean ± SEM: RER_{peak15} = 1.081 ± 0.007; RER_{peak30} = 1.073 ± 0.007; RER_{peak60} = 1.065 ± 0.007). Overwhelmingly runners failed to reach an RER_{peak} ≥1.10 for RER_{peak15} (63.3%), RER_{peak30} (66.7%) and RER_{peak60} (70%). $VO_{2peak30}$ and RER_{peak30} were not related for female ($r = 0.36$; $p = 0.21$) or male ($r = -0.07$; $p = 0.81$) runners.

Conclusions: Either current RER_{peak} guidelines are not low enough to prevent mass secondary confirmation marker misclassifications or approximately two-thirds of participants terminated their GXT without giving maximal effort. If the former is believed, an RER_{peak30} threshold of ≥ 1.03 would have classified all but one participant as having exerted maximal effort. This may be a more suitable cut-off point to confirm GXT validity in high-training volume, competitive female and male runners with VO_{2peaks} ≥ ~50 and 60 ml/kg/min, respectively.

Key Words: VO_{2max}, endurance athlete, aerobic capacity

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Introduction

Maximal (or peak) oxygen uptake ($VO_{2max/peak}$) is commonly used as an index of cardiorespiratory fitness in the general population[1-3] and as a predictor of aerobic endurance performance in trained athletes[4-6]. Seminal running investigations[7,8] established a valid VO_{2max} would exhibit an increase in work rate and plateau or fall in oxygen uptake with continued increase in running speed or grade. However, there is no universal agreement on what constitutes a plateau[9], and a significant portion of participants will fail to exhibit plateau characteristics[10-12]. These factors create challenges in confirming the validity of a graded exercise test (GXT). VO_{2peak} is also often designated as the descriptor of aerobic capacity during a GXT, as there is less stringent requirement of a confirmation of plateau. Regardless of nomenclature, it is a necessity that the participant gives *maximal effort* during a

GXT for accurate assessment. A combination of surrogate measures, such as percentage of maximal heart rate, lactate concentration, and respiratory exchange ratio (RER) have been suggested as indicators that maximal effort was achieved by the participant during a GXT, and $VO_{2max/peak}$ outcomes are valid.[13]

Of these options, RER is both non-invasive and considered the most valid measure that a participant completed a GXT with maximal effort.[14] Peak RER (RER_{peak}) at the end of a GXT in recreationally competitive male runners was recently reported to have a highly favorable coefficient of variation of only 1.3%.[15] Measuring RER during an exercise bout provides information regarding substrate utilization indirectly via the lungs.[16] On the cellular level, the ratio of produced CO_2 and utilized O_2 is termed the respiratory quotient and is assessed invasively through use of arterial and venous catheters.[17] Both respiratory quotient and RER values are dictated by exercise intensity. Respiratory quotient values demonstrating the extremes of fat and carbohydrate oxidation range from 0.70 to 1.00, respectively.[18,19] In contrast, during the late stages of a GXT, RER values can exceed 1.00 as circulating VCO_2 levels accumulate from a major shift to non-oxidative carbohydrate dependent metabolism.[20-22]. As exercise intensity increases, anaerobic glycolysis and hydrolysis of adenosine triphosphate increase H^+ production. After passing through the myocyte membrane, extracellular H^+ buffering occurs primarily via bicarbonate and to a lesser extent non-bicarbonate factors (e.g. hemoglobin and phosphates).[23] Variance of intracellular H^+ production and extracellular buffering capacity can produce a substantial range of RER_{peak} for individuals at the end of a GXT. Because of the influence of myofibril composition, this is potentially problematic in quantifying what RER_{peak} criterion is suitable as a secondary confirmation factor for establishing if maximal effort was achieved during a GXT in endurance trained athletes.

Issekutz and Rodahl [24] led one of the earliest studies examining the association between RER values and VO_{max}. During discontinuous cycle ergometer testing, mean RER_{peak} was reported at 1.19 for a group of 19 non-endurance trained participants. Contemporary GXT protocols most commonly use an RER_{peak} criterion recommended by the American College of Sports Medicine[25] of $\geq$1.10. However, the current authors are unaware of formal efforts to establish if this popular RER_{peak} criterion is appropriate for competitive runners, who would be expected to generate lower VCO_2 and therefore lower RER from acid buffering during a GXT than their untrained counterparts. Therefore, the primary purpose of this study was to evaluate whether National Collegiate Athletics Association (NCAA) Division I cross-country runners consistently achieve the $\geq$1.10 RER_{peak} criterion during the last 2 min of a GXT. Additional consideration was given for effects of sampling intervals (15-, 30-, and 60-s) and sex. Data were explored to determine whether a lower threshold may be more appropriate.

Scientific Methods

Participants

The success of the current study was dependent on the ability to recruit well-trained runners who were accustomed to extreme fatigue during running and homogeneous in ability relative to sex. A maximal sample of convenience was recruited via personal and team communications after coach approval was granted for NCAA Division I cross-country runners from two universities. Sixteen male and fourteen female runners volunteered to participate in this study. Competition 8-km and 5-km (conference championship and regional race distances for both teams) distance personal bests from the previous season were 26.13 ± 1.24 min and 19.03 ± 0.97 min for the male and female runners, respectively. Participants were 18 years or older and free of any musculoskeletal injuries that could influence running performance at the time of data collection. Greater detail concerning the participants' performance capacity, other physiological variables, and running profiles can be found in Carder et al.[26] and O'Neal et al.[27] Anthropometric data, including height (males 178 ± 3 cm; females 162 ± 9 cm) and body mass (males 64.8 ± 5.2 kg; females 54.6 ± 3.8 kg), were assessed using a stadiometer (Invicta Plastics Limited, Leicester, England) and digital scale (BWB-800; Tanita, Inc., Tokyo, Japan). Participants provided written informed consent and completed a pre-participation health screening questionnaire. The local institutional review board at each university approved this study.

Protocol

On the day prior to testing, participants were asked to refrain from strenuous exercise and abstain from caffeine and alcohol consumption. Morning session participants arrived at the laboratory after an overnight fast. Afternoon session participants were required to arrive at least 3-h postprandial. Participants completed their own habitual warm-up protocol. For most participants this consisted of various combinations of leg swings, high knees, skips, walking hamstring stretches, and strides prior to the GXT performed on a rubberized-slat belt treadmill (4Front, Woodway, Waukesha, WI). The highest 30-s SI during the last 2 min of the test was deemed $VO_{2peak30}$ (female = 53.9 ± 2.8 ml/kg/min; male = 69.2 ± 3.8 ml/kg/min). RER data were collected from the GXT protocol developed in our laboratory with intensity primarily altered via treadmill velocity rather than grade to best suit trained distance runners and elicit volitional fatigue in ~8–12 min. The incremental running protocol consisted of a starting velocity 2.4 km/h less than each runner's self-estimated 5-km pace. Velocity increased by 0.8 km/h every two minutes until volitional exhaustion was incurred. The initial treadmill grade was set at 1% and was maintained unless a speed of 19.3 km/h was reached. If participants reached this velocity, the grade increased by 1% every 2 min. Strong verbal encouragement was given to the participants by multiple data collectors for every GXT. The metabolic cart (TrueOne2400, Parvo Medics Inc., Sandy, UT) used was calibrated to the manufacturer's specifications. Unfiltered, averaged breath-by-breath data for RER and VO_2 were saved and printed in SI of 15-, 30-, and 60-s. RER_{peaks} within the final 2 min of the GXT were visually searched and recorded by separate members of the investigative team, then compared for accurate confirmation of RER_{peak} at each SI.

Statistical Analysis

Distribution of RER_{peak} within each SI for males, females, and all participants was assessed and confirmed ($p > 0.05$) for normality using Shapiro-Wilk test procedures. Individual, repeated measures ANOVA within samples (i.e. male, female, and all participants) was used to determine if RER_{peak} differed among SI. Sphericity amongst the groups was determined by Mauchly's test, and Greenhouse-Geisser adjustments were made in cases where sphericity was violated. Bonferroni corrections were made for pairwise comparisons if a main effect for SI was found. Independent samples *t* tests were used to compare RER_{peak} between sexes for each SI. Manual counts were used to determine the number and percentage of RER_{peak} that reached the popular 1.10 criterion marker within each sex for each SI. Relationship between $VO_{2peak60}$ and RER_{peak60} within sex was determined using bivariate correlation. IBM SPSS Statistics v. 26 was used to conduct all analyses (v. 26; IBM, Chicago, IL).

Visual inspection of individualized RER_{peak} data across SI was used by the investigative team to determine if a new, lower criterion RER_{peak} is warranted. Potential recommendations were made to minimize false positive and negative misclassifications with a novel, lower RER_{peak} criterion versus an RER_{peak} criterion of ≥1.10.

Results

There were no differences between sexes for any SI (Table 1). When RER_{peak} data for each sex were combined, there was a main effect for SI ($p < 0.001$; $\eta p^2 = 0.52$). Post hoc testing revealed each SI differed with the expected trend that lowering SI would increase RER_{peak} (Table 1). Within sex, RER_{peak15} was higher than RER_{peak30} and RER_{peak60} for female participants, and RER_{peak15} was higher than RER_{peak60} for male participants (Table 1). Only female RER_{peak15} 95% CI reached or exceeded upper limits of 1.10 (Table 1). Figure 1 displays individual RER_{peak15}, RER_{peak30}, and RER_{peak60} for both male and female runners. A dashed line representing the 1.10 RER criterion has been imposed on the figure for reference. Less than 40% of both male and female runners reached the criterion RER_{peak} value of 1.10 for each SI (Table 2). Shortening the SI from 60-s to 15-s only resulted in 1 male and 1 female runner increasing their RER_{peak} from less than 1.10 to meeting or exceeding the 1.10 threshold. There was no significant relationship ($p > 0.05$) between $VO_{2peak30}$ and RER_{peak30} for female or male cohorts (Figure 2).

Table 1. Peak respiratory exchange ratio (RER_{peak}) values for male ($n = 16$), female ($n = 14$), and all collegiate cross-country runners. Data displayed as mean±SEM [95% CI].

	RER_{peak15}	RER_{peak30}	RER_{peak60}
All	1.081±0.007 [1.067, 1.095]^{b,c}	1.073±0.007 [1.060, 1.087]^{a,c}	1.065±0.007 [1.050, 1.079]^{a,b}
Female	1.089±0.009 [1.070, 1.109]^{b,c}	1.079±0.009 [1.060, 1.097]^{a}	1.074±0.009 [1.053, 1.094]^{a}
Male	1.074±0.001 [1.052, 1.095]^{c}	1.069±0.010 [1.047, 1.090]	1.057±0.010 [1.035, 1.079]^{b}

^{a} $p < 0.05$ vs RER_{peak15}; ^{b} $p < 0.05$ vs RER_{peak30}; ^{c} $p < 0.05$ vs RER_{peak60}.

Table 2. Instances in which peak respiratory exchange ratio (RER_{peak}) values reached 1.10 criterion marker in each sampling interval. Data displayed as number of cases (% of cases).

	RER_{peak15}	RER_{peak30}	RER_{peak60}
All ($n = 30$)	11 (36.7)	10 (33.3)	9 (30.0)
Female ($n = 14$)	6 (42.9)	5 (35.7)	5 (35.7)
Male ($n = 16$)	5 (31.3)	5 (31.3)	4 (25.0)

Visual observation of the data led the investigative team to propose a potential RER_{peak} of ≥1.03 as a more appropriate minimal criterion that maximal effort has been achieved during a GXT in trained female and male runners with VO_{2peak} of approximately 50-60 and 63-75 ml/kg/min, respectively (Figures 1 & 2). SI is likely important in regard to RER_{peak}.

Using RER_{peak15} and RER_{peak30}, only 1 participant failed to reach this novel criterion. Five participants fell below the 1.03 threshold when SI was extended to the more conservative RER_{peak60} (Figure 1).

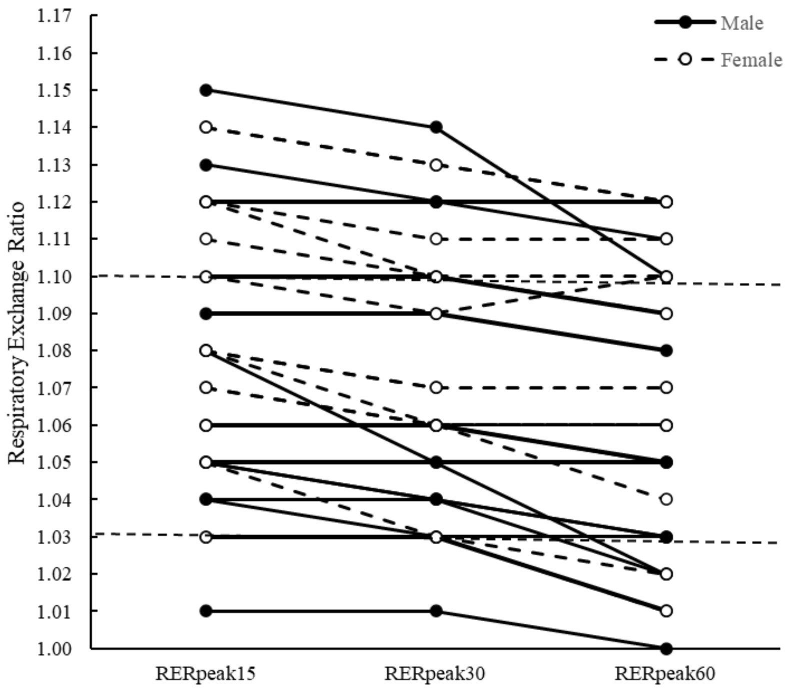

Figure 1. Individual peak respiratory exchange ratio (RER_{peak}) at each sampling interval. Shared data points are shown as mixed lines or markers Horizontal dashed lines represent traditional (top) and proposed (bottom) cutoff criteria for RER_{peak60}.

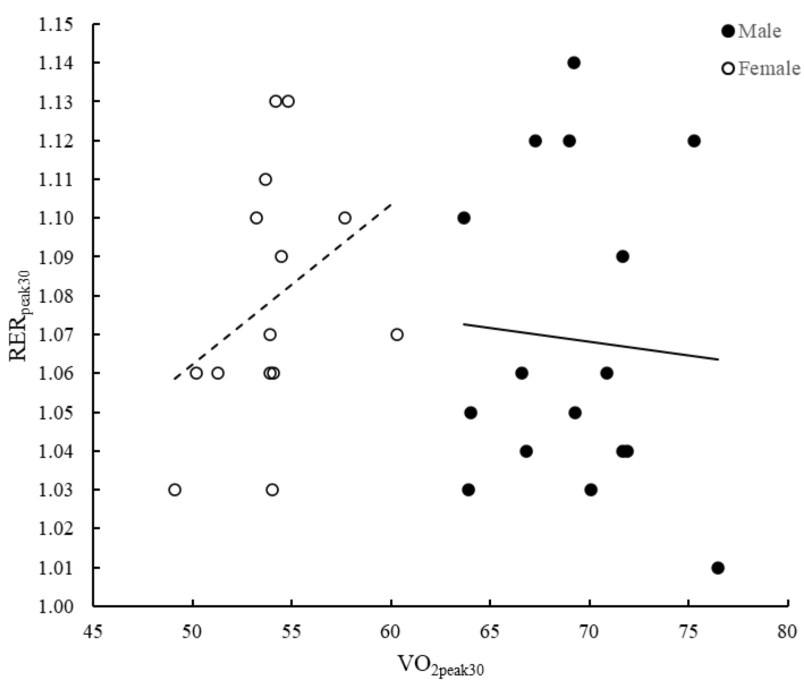

Figure 2. Relationship between 30-s peak oxygen uptake ($VO_{2peak30}$) and 30-s peak respiratory exchange ratio (RER_{peak30}) for female (r = 0.36, p = 0.21) and male (r = -0.07, p = 0.81) runners.

Discussion

RER_{peak} is the most valid, objectively measured secondary confirmation marker of maximal effort evidence during a GXT. Impetus for the current study was based on years of anecdotal observations of collegiate cross-country runners in our laboratories, giving admirable effort but failing to meet the ≥ 1.10 RER_{peak} criterion. The main finding of this study is the confirmation of the need for revised RER_{peak} criteria as a secondary confirmation that maximal effort was achieved during a GXT for higher performing distance runners. RER_{peak} did not differ between male and female NCAA Division I cross-country runners, and only 30-37% (depending on SI) of participants met the popular 1.10 RER_{peak} criterion. Reducing from the longest (RER_{peak60}) to the shortest (RER_{peak15}) SI only resulted in 2 additional participants achieving an RER of 1.10. Visual inspection of the data revealed lowering the RER criterion to ≥1.03 and using RER_{peak15} or RER_{peak30} would have resulted in 97% of runners meeting the proposed secondary confirmation threshold. Suggestions were made under the assumptions: (1) that all participants in the current sample exhibited maximal effort and (2) the current sample's RER_{peak} values were representative of trained, competitive runners with similar aerobic capacities to our participants.

Edvardsen, Hem and Anderssen [9] performed the most comprehensive (n = 861; ages 20-85 years) investigation for global RER criterion validation to date. The authors determined that age, but not sex, should be considered a factor when interpreting RER_{peak30} as a secondary GXT confirmation criterion during a modified Balke treadmill protocol. The current outcomes support the general population conclusion that sex also fails to influence RER_{peak} in trained, competitive runners. In regard to age, Edvardsen and colleagues[9] suggested an RER_{peak} criterion of ≥1.10 for participants ages 20-49 years. RER_{peak} of the youngest (20-34 years) general population male (1.23 ± 0.10) and female (1.21 ± 0.10) pools reported by Edvardsen, Hem and Anderssen [9] exceeded the current study's participants' most liberal cumulative SI RER_{peak15} by 0.15 and 0.13 units, respectively (Table 1 & Figure 1).

In regard to trained populations, the current authors are unaware of any studies directly exploring the relationship between running performance or aerobic capacity and RER_{peak} in a heterogenous pool of only trained endurance athletes. We are also unaware of studies intentionally comparing RER_{peak} characteristic differences between endurance trained versus non-endurance trained athletes. Type IIa fibers have superior intracellular buffering abilty[28] and can improve their own buffering capacity with high intensity training.[29] However, Type IIa muscle fibers also produce H^+ to a much greater extent than Type I fibers. Type IIa fibers have the capacity to decrease intramuscular pH to ~6.2 compared to only ~6.9 in Type I fibers during exercise at or above $VO_{2max/peak}$.[28] Ultimately, CO_2 exceeding that directly produced via aerobic metabolism, which can result in RER exceeding 1.00, must be buffered extracellularly primarily through the bicarbonate system. If all other factors were nullified, a higher Type I muscle fiber percentage should result in a lower rate of circulating VCO_2 to be exchanged at the lungs at the end of a GXT (i.e. a lower RER_{peak}). Whether through genetic predisposition or years of endurance style training, the participants in the current study would be expected to exhibit a higher percentage of Type I muscle fibers than runners of lesser abilities or non-endurance trained athletes. Accordingly, a reduced RER_{peak} capacity at the end of a GXT compared to such groups was indeed confirmed.

Several studies with trained participants stand out for their comparative evidence to the current findings that a novel RER_{peak} criterion designation is needed for well-trained distance runners. In the first, Eryilmaz and Polat[31] reported an RER_{peak} of 1.19 ± 0.03 for 13 nationally or internationally competitive male alpine skiers. The authors defined their participants as "anaerobic-trained athletes" with mean RER_{peak} akin to that of general population young adults [9] and ~0.12 units higher than the current study's male runners. The alpine skiers' VO_{2max} of 54.2 ± 6.0 ml/kg/min is representative of recreationally competitive male runners[32] but not more advanced runners. Every skier exhibited RER_{peak} ≥1.15 during the treadmill GXT with exception of one participant. Interestingly, this was also the only participant within the cohort who had a VO_{2max} greater than 65 ml/kg/min. No male participant in the current study had a VO_{2peak} less than 63 ml/kg/min, nor did any participants exceed an RER_{peak} of 1.15. An influential secondary confirmation criteria study by Poole, Wilkerson, and Jones[33]recommended abandoning the 1.10 criterion. In a unique interpretation of their data, the authors[33] raised concern that if the cycling ramp test in their study was terminated at an RER of 1.10, individual $VO_{2max/peak}$ would have been underreported by as much as 27%. We are unaware of real-world practice or formal suggestions of terminating a GXT at a pre-established RER_{peak}, but the comparison of participants between this study and ours is critical to note. Poole, Wilkerson, and Jones[33]participants were only recreationally active and not "highly trained" according to the authors' description. No relative $VO_{2max/peak}$ information was provided. Seven of their eight healthy, young adult male participants exceeded an RER of 1.19. Again, none of the current participants exceeded 1.15 (Figure 2), further supporting the need for a distinct RER_{peak} criterion for trained distance runners. While not intended as a key dependent variable, description of RER_{peak} in world-class Kenyan 10-km runners is provided by Billat, Lepretre, Heugas, Laurence, Salim and Koralsztein [6]. Three sub-groups of elite runners homogeneous in ability but with different training programming emphases completed a track-based GXT. RER_{peak} for the first two sub-groups whose coaches emphasized training intensity versus volume was reported by sex for 6 male (1.03 ± 0.03) and 6 female (1.04 ± 0.04) runners. Similar values were found in an additional sub-group of 6 male runners (1.05 ± 0.04) whose programming placed greater emphasis on volume versus intensity. These values are closer, but even lower, than our well-trained but less elite runners. Intriguingly, the only runner in the current study that failed to reach 1.03 for any SI (lowest set of scores in Figure 1) was also the runner with the highest $\dot{V}O_{2peak}$ (lowest marker to the right in Figure 2). Collectively, these outcomes highlight that there is a currently unknown or defined $\dot{V}O_{2peak/max}$ threshold in endurance trained individuals that needs to be reached before markedly lower RER_{peak} becomes the rule versus the exception.

The investigation by Eryilmaz and Polat[31]described in the previous paragraph is the only contemporary study we are aware of that intentionally examined the correlation of RER_{peak} and $\dot{V}O_{2peak/max}$. RER_{peak} in the group of trained but non-endurance trained athletes was strongly and inversely (r = -0.71) related to $\dot{V}O_{2max}$. The strong inverse relationship was not replicated in our male or female distance runners (Figure 2). No formal relationship analyses between RER_{peak} and $\dot{V}O_{2max/peak}$ were conducted for the elite Kenyan runners in Billat et al.[6], but the three subgroups specifically assigned due to their different endurance training philosophies all displayed similarly low RER_{peak} means and tight variance regardless of training focus type. This is important as it supports that runners of high, similar abilities but different training programs are unlikely to be differentiated by RER_{peak} just as a higher $\dot{V}O_{2peak}$ was not indicative of a lower RER_{peak} in the homogenous groups of runners in the current study. If RER_{peak}-specific guidelines for the endurance athlete population are promoted, there is need for evidence of robustness in the lowered criterion with regards to factors such as age, years of experience, and training volume and programming. The current sample size and composition do not allow for all these considerations, but a relative $\dot{V}O_{2max/peak}$ in the mid- to low- 60's for male runners might be a good starting criterion threshold for novel RER_{peak} designation. There is less sex-based data for comparison, but a threshold of ~50 ml/kg/min might serve as a starting point for identifying female distance runners expected to have a depressed RER_{peak} capacity. The same concerns hold true for what the novel RER_{peak} criterion should be, but 1.03 for RER_{peak15} or RER_{peak30} is the most obvious choice to limit misclassifications under the assumption all participants provided maximal effort in the current study.

There are multiple limitations of the current study. The first is interpretation of the current data is only intended to apply to a traditional, continuous-style GXT. Short verification tests exceeding the highest intensity achieved during a traditional GXT or ramp protocol were once proposed as the solution to using secondary confirmation markers or plateau characteristic assessments to confirm GXT validity. While meta-analysis does not support supra-maximal verification tests resulting in higher $\dot{V}O_{2max/peak}$[34], verification test design can greatly influence RER_{peak}. Sánchez-Otero, Iglesias-Soler, Boullosa and Tuimil[32] recruited 12 recreationally competitive, male runners to complete a track-based GXT (1 km/h velocity increases every 2 min) and a separate verification test that resulted in exhaustion in ~3-4 min. The verification test protocol increased RER_{peak} from 1.16 ± 0.07 to 1.24 ± 0.11. Caution should be taken when applying the current findings for RER_{peak} to verification test scenarios. Although the study required a universal 24-h rest period the day before testing, it was not possible to control or standardize the training schedules of our collegiate athlete participants beyond this timeframe. It is possible normal daily training induced fatigue accumulated at different rates for participants prior to their rest days. We had great support from the coaching staff for this project, but logistically we could only test a single participant at a time. As such, investigators attempted to make laboratory sessions as widely available as possible working around the teams' training schedules. Potential diurnal variation was not accounted for, and only a 3-hour fast was required for the experimental sessions that occurred after midday.

Conclusions

Many studies with endurance-trained athletes implement protocols in which two or more secondary confirmation factors (e.g. heart rate max, rate of perceived exertion, and RER) are used to confirm an achievement of maximal effort during a GXT. The current study suggests that using this model with an RER_{peak} of ≥1.10 is not acceptable for highly trained, competitive runners during a traditional style GXT. The current authors requested participants run to volitional exhaustion as the termination criterion for the GXT. There are two simple scenarios that likely explain the inability of approximately 2/3 of these runners to meet the 1.10 criterion. The first is that these participants failed to reach an RER_{peak} of 1.10 because maximal effort was not given. The second is that the runners' physiological characteristics prevented gas exchange measured at the lung and respiratory tract level to exceed RER_{peak} values ≥ 1.10. In support that the latter is the most plausible scenario, we suggest the following based on the current preliminary findings: For competitive, high-volume female and male runners exhibiting $VO_{2peak/max}$ > 50 and 60 ml/kg/min, respectively, RER_{peak} criterion should be assessed in SI of 15-30 s and lowered to ≥ 1.03. It is important to note that these results from a homogenous group of trained runners do not contradict recommendations for non-endurance-trained individuals. Additional confirmation of these outcomes is needed to solidify the current recommendations.

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