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Research article

Higher precision of heart rate compared with VO_2 to predict exercise intensity in endurance-trained runners

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Abstract
The aim of the present study was to assess the precision of oxygen uptake with heart rate regression during track running in highly-trained runners. Twelve national and international level male long-distance road runners (age 30.7 ± 5.5 yrs, height 1.71 ± 0.04 m and mass 61.2 ± 5.8 kg) with a personal best on the half marathon of 62 min 37 s ± 1 min 22 s participated in the study. Each participant performed, in an all-weather synthetic track five, six min bouts at constant velocity with each bout at an increased running velocity. The starting velocity was 3.33 $m \cdot s^{-1}$ with a 0.56 $m \cdot s^{-1}$ increase on each subsequent bout. VO_2 and heart rate were measured during the runs and blood lactate was assessed immediately after each run. Mean peak VO_2 and mean peak heart rate were, respectively, 76.2 ± 9.7 $mL \cdot kg^{-1} \cdot min^{-1}$ and 181 ± 13 $beats \cdot min^{-1}$. The linearity of the regressions between heart rate, running velocity and VO_2 were all very high ($r > 0.99$) with small standard errors of regression (i.e. $Sy.x$ < 5% at the velocity associated with the 2 and 4 $mmol \cdot L^{-1}$ lactate thresholds). The strong relationships between heart rate, running velocity and VO_2 found in this study show that, in highly trained runners, it is possible to have heart rate as an accurate indicator of energy demand and of the running speed. Therefore, in this subject cohort it may be unnecessary to use VO_2 to track changes in the subjects' running economy during training periods.

Key words: Running velocity, internal load, relationships, standard error.

Introduction

The most common procedure to assess the energy demand during physical activities is indirect calorimetry based upon the oxygen uptake (VO_2) measurement. However, the majority of professionals that work in sports do not have easy access to gas analysers, which can justify the attempt to validate other measurements to estimate energy demand. The use of modern technology, such as accelerometers, attempted to overcome those difficulties (Schmitz et al., 2005; Fudge et al., 2007). However the cost of high-technology accelerometers may override their election as indirect energy demand estimators. Moreover, the validity of these instruments has often been questioned (Leenders et al., 2003; 2006) and description of high precision is limited to some types of exercise with specific populations (Kozey et al., 2010). In animal studies the VO_2 / heart rate relationship is vastly used to assess the energy demand during locomotion (Brosh, 2007; Halsey et al., 2008) and it has also been investigated in humans (Hiilloskorpi et al., 1999; Garet et al., 2005). The VO_2 / heart rate relationship is often used in the medical field (Mezzani, et al., 2007) or to assess children's physical activity (Iannotti et al., 2004) but less in the sports training field (Vella and Robergs, 2005).

In exercise prescription, other than the energy demand estimations, heart rate measurements provide a useful tool to prescribe exercise intensity and monitor training adaptations. In this context, some have attempted to provide evidence from the relationship between fractions of heart rate reserve and fractions of VO_2 reserve (Lounana et al., 2007). Indeed, the most commonly used measurement to control exercise intensity is the heart rate. Heart rate monitors are less costing than other instruments and both data collection and interpretation is easy for most athletes and coaches. The potential of heart rate to be used as a valid exercise intensity indicator warrants the establishment of the individual relationship between VO_2 and heart rate and the precision of this technique depends on the robustness of the regression line. The precision of the VO_2 / exercise intensity regression is well-described and accepted during treadmill running (Reis et al., 2007) or running on a track (Reis et al., 2004). However, the literature presents less evidence to confirm the robustness of regression models between VO_2 and heart rate during running (Hiilloskorpi et al., 1999).

In our opinion, in the few studies that have addressed the VO_2 / heart rate regression issue, little attention has been given to the standard error of the regressions. Indeed the use of correlation coefficients to interpret the regression is quite limited if not unadvisable. In sports training, coaches need to quantify the variation (absolute and relative errors) that derives from the use of heart rate as an exercise intensity indicator.

Despite a large number of studies on physiology that are present in the literature addressing long-distance running, we found no study quantifying the precision of the VO_2 / heart rate regression line among highly-trained long-distance runners. Therefore the aim of the present study was to assess the precision of VO_2 with heart rate regression during track running performed by highly-trained runners.

Methods

Participants

Twelve male subjects volunteered for this study after medical approval. The participants were national and

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international level long-distance roadrunners (half-marathon and marathon) and they were all involved in systematic endurance training programs. Their mean age, years of systematic training, height and body mass were, respectively: 30.7 ± 5.5 years, 16.2 ± 5.2 years, 1.71 ± 0.04 m and 61.2 ± 5.8 kg. The subjects' best performance at half-marathon was 62 min 37 s ± 1 min 22 s and their last best performance (within a period of up to 6 months prior to the study) was 63 min 19 s ± 1 min 15 s. The subjects gave their written informed consent to participate in the experiment and all the procedures were approved by the local ethics committee.

Testing

Field-testing was conducted on a 400-m all-weather synthetic track. Tests were performed with a temperature ranging from 16 to 20 degrees Celsius and humidity between 45 and 55%. The subjects were asked to refrain from high-intensity training during the three days previous to the test.

Each subject performed several six min bouts at a constant velocity. The running velocity of the subjects was kept constant by a cyclist using an electromagnetic speedometer bicycle and the subjects were instructed to follow him at a safe distance, between 1 and 1.5 m. The starting running velocity was 3.33 $m{\cdot}s^{-1}$. Each subsequent bout was performed with a velocity increase of 0.56 $m{\cdot}s^{-1}$. The recovery time between bouts was individual and based on heart rate and VO_2 measurements during the recovery. Subjects were allowed to start a new bout, when during a one-min period, heart rate and VO_2 were less than 5 $beats{\cdot}min^{-1}$ and less than 2 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ respectively different from the value observed before the beginning of the first bout. The test was ended by voluntary exhaustion of the subject. The highest VO_2 mean value averaged over 20 s was taken as the subject's peak VO_2. Through all testing expired gases were collected and analysed with a K4 b2 gas analyser (Cosmed, Rome, Italy) and VO_2 was averaged in 20 s intervals. Before each test, a reference air calibration of the device was performed using a known gas standard of 16% O_2 and 5% CO_2 concentration. The flow meter was also calibrated before each testing with a 3000 mL syringe. Heart rate was recorded continuously with a RS800 device (Polar Electro, Finland) and averaged over 20 s intervals. The highest heart rate mean value averaged over 20 s was taken as the subject's peak heart rate. Ear lobe capillary blood sample collections were made immediately after each bout to assess blood lactate concentration using an Accusport Lactate Analyser (Boehringer, Mannheim, Germany). Before each testing, a calibration of this device was performed, using YSI 1530 Standard Lactate Solutions (2.5, 5, 10 and 15 $mmol{\cdot}L^{-1}$). Blood lactate accumulation was identified by linear interpolation for determination of the running velocity corresponding to the 2 and 4 $mmol{\cdot}L^{-1}$ thresholds (V_2 and V_4 respectively).

Linear regressions

The exercise bouts were performed in order to obtain VO_2 / heart rate relation points that enabled the calculation of a valid regression equation. For each velocity, mean heart rate and mean VO_2 over the last minute of the bout was used for this purpose and VO_2 was taken as the dependent variable. All the subjects completed five full bouts. Most subjects (n=9) performed a sixth bout but this was not included in the regression, as it failed to comply with the VO_2 steady-state attainment (determined as a difference of less than 2 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ between two consecutive minutes) or could not be maintained for the six min duration. Linear regressions with the running velocity as independent variable and VO_2 or heart rate as dependent variables were also established. A zero velocity VO_2 (mean 1 min value recorded before the start of the sub maximal test) was included in the VO_2 / velocity regression lines by a non- forced procedure (Reis et al., 2005). As to the heart rate / velocity regression, a zero velocity heart rate was also included. For this purpose the subjects' average one min heart rate prior to the start of the first bout (without any previous exercise) was taken. In the heart rate /VO_2 regression lines the resting VO_2 and heart rate were also included in the regressions.

Statistical analysis

Data was analysed with SPSS 14.0 (SPSS Science, Chicago, USA) software. Normality assumption was checked with the Shapiro-Wilk test. Simple linear regressions were used on all data. The scatter around the regression line was used a measure of the fitness of the regression lines. The statistical significance was set to $p \leq 0.05$. The results are presented as means ± standard deviations (SD).

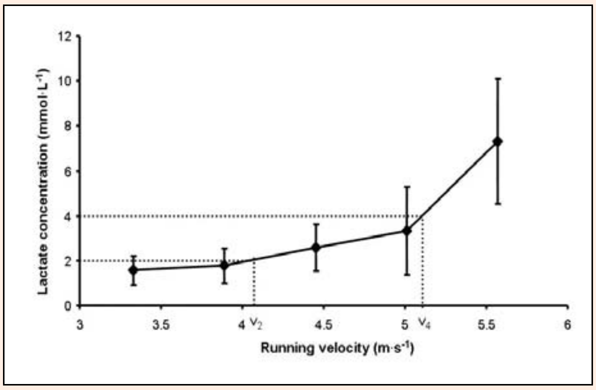

Figure 1. Average lactate concentrations after each running bout. Velocity at 2mmol·L^{-1} and 4 mmol·L^{-1} expressed as v_2 and v_4.

Results

Mean peak VO_2 and mean peak heart rate were, respectively, 76.2 ± 9.7 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ and 181 ± 13 $beats{\cdot}min^{-1}$. Mean velocity at the 2 $mmol{\cdot}L^{-1}$ threshold (V_2) was 4.04 ± 0.50 $m{\cdot}s^{-1}$ and at the 4 $mmol{\cdot}L^{-1}$ threshold (V_4) it was 5.10 ± 0.40 $m{\cdot}s^{-1}$. The subjects performed on average two running bouts below V_2, a 3rd bout between V_2 and V_4, a 4th bout with intensity close to V_4 and a fifth bout above V_4. The mean blood lactate values in the five bouts were shown in Figure 1. The regressions between the heart rate, running velocity and VO_2 were all significant ($p < 0.01$), with high linearity ($r > 0.99$) and with a small standard error of regression ($Sy.x \leq 4.51$) as depicted in Figures 2, 3 and 4. These figures show the squared correlation coefficient (R^2), the standard error of regression (*Sy.x*) as well as the regression equation traced with the mean data from all the participants.

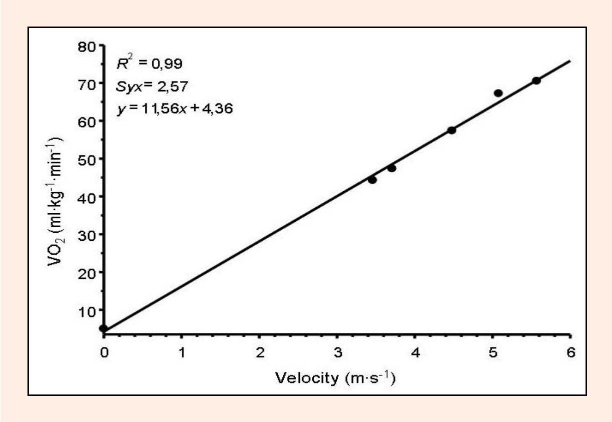

Figure 2. Linear regression between VO_2 and running velocity (n = 12).

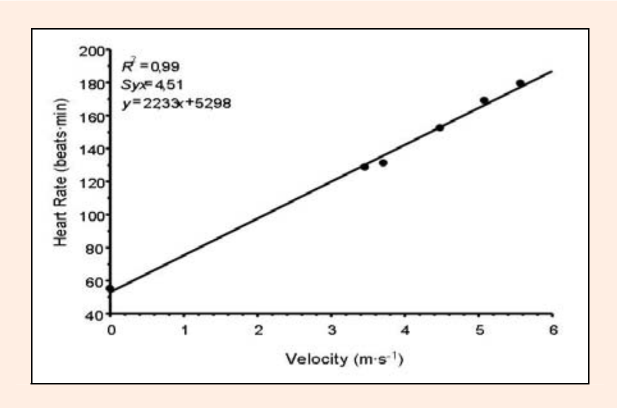

Figure 3. Linear regression between heart rate and running velocity (n = 12).

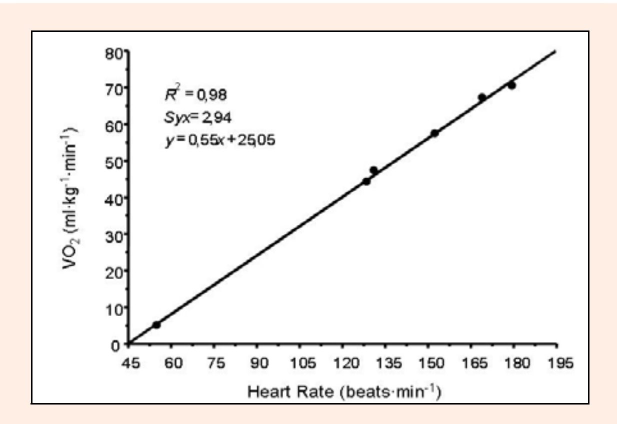

Figure 4. Linear regression between VO_2 and heart rate (n = 12).

Discussion

The aim of the present study was to assess the precision of heart rate / oxygen uptake regression during track running performed by highly-trained runners. The main findings were that the heart rate correlated strongly and with low standard error both with the oxygen uptake and with running velocity.

The last bout of exercise (6^{th}) for 9 subjects was performed at 6.13 m.s^{-1} (≈22 km·h^{-1}). Using the VO_2 / velocity regression the calculated VO_2 was 75.2 mL·kg^{-1}·min^{-1}, which corresponded to the subjects' peak VO_2 of 76.1 mL·kg^{-1}·min^{-1}. This running velocity (≈22 km·h^{-1}) should be close to the subjects' maximal aerobic velocity and may suggest that the athletes achieved a peak VO_2 value close to their true maximum. The same applies to the peak heart rate that was observed. The mean value was ≈10 beats·min^{-1} below the age-predicted maximum (220-age). The mean heart rate that was derived by interpolation at V_2 and V_4 was ≈85% and ≈91% of the subjects' peak heart rate, respectively. The mean VO_2 calculated at the same thresholds was ≈74% and ≈81% of the subjects' peak VO_2, respectively. Thus, the fraction of-peak heart rate was ≈10% higher than the fraction of peak VO_2 elicited at V_2 and V_4, which confirms previous findings in trained cyclists (Mamen and van den Tillaar, 2009) and runners (Mamen et al., 2010). Mean running velocity at the 4 mmol·L^{-1} threshold (V_4) was within the literature reports for high-performance endurance trained runners (Bragada et al., 2010).

The mean variation in the VO_2 / running velocity regression was 2,6 ± 0,9 mL·kg^{-1}·min^{-1}. This variation represents a relative error of ≈4,6% and ≈4,2%, considering the VO_2 that was observed at V_2 and V_4, respectively. The variation in the present study is slightly above that reported for sprint-trained (Reis et al., 2004) and endurance-trained (Reis et al., 2005) athletes, performing respectively on a track and on a horizontal treadmill. The mean variation of the heart rate / running velocity regression was 5 ± 3 beats.min^{-1}. This variation represents a relative error of ≈2,95% and ≈2,75%, considering the heart rate that was calculated for V_2 and V_4, respectively.

By having the heart rate as independent and the VO_2 as dependent variable, we investigated how much the heart rate could reflect true energy demand (VO_2). The model presented a mean error of regression of 2,9 ± 1,0 mL·kg^{-1}·min^{-1}. At V_2 and V_4, heart rate predicted VO_2 with a relative error of ≈ 5% and ≈ 4,5%, respectively. Our results are contrary to those reported by Vella and Robergs (2005) with endurance-trained subjects during cycling. The literature presents evidence on the non-linearity of the VO_2 / heart rate relationship at very low or very high exercise intensities (for references see Achten and Jeukendrup, 2003). Our results indicate that in highly-trained endurance runners it is possible to observe the linearity up to exercise intensities as high as 90% peak VO_2. The high linearity may be partially due to the fact that the factors, which typically explain the deviations from linearity (for references see Achten and Jeukendrup, 2003) may be nonexistent or negligible in this type of population. Another issue that can help to explain the high linearity in our subjects is the fact that only steady-state VO_2 with duration of 6-min bouts were included in the regressions. In fact, it has been shown that quick transitions between intensities (short-duration exercise bouts) do account for the non-linearity of the VO_2 / heart rate relationship (Jeukendrup et al., 1997; Vachon et al., 1999).

The range of intensities assessed in the present study cover the majority of those commonly used in the training process of middle- and long-distance runners. Indeed, from a practical point of view V_2 and V_4 represent exercise intensities, which are typically used to prescribe endurance training and for that reason we focused our analysis at those thresholds. The results of the present study show that, in highly trained runners, it is possible to use heart rate as an accurate index of the external load during sub maximal running speeds. Hence, the need to assess the subjects VO_2 response to exercise may not be that important for exercise prescription purposes.

Conclusion

The strong relationships between heart rate, running velocity and VO_2 found in this study shown that, in highly-trained runners, it is possible to have heart rate as an accurate indicator of energy demand and of the running speed. Therefore, in this subject cohort it may be unnecessary to use VO_2 to track changes in the subjects' running economy during training periods.

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Key points

- Heart rate is used in the control of exercise intensity in endurance sports.
- However, few studies have quantified the precision of its relationship with oxygen uptake in highly trained runners.
- We evaluated twelve elite half-marathon runners during track running at various intensities and established three regressions: oxygen uptake / heart rate; heart rate / running velocity and oxygen uptake / running velocity.
- The three regressions presented, respectively, imprecision of 4,2%, 2,75% and 4,5% at the velocity associated with the 4 $mmol \cdot L^{-1}$ threshold.
- The results of the present study show that, in highly trained runners, it is possible to use heart rate as an accurate index of the external work rate during sub maximal running speeds.

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