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10 km Running Performance Predicted by a Multiple Linear Regression Model with Allometrically Adjusted Variables

by
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The aim of this study was to verify the power of VO_{2max}, peak treadmill running velocity (PTV), and running economy (RE), unadjusted or allometrically adjusted, in predicting 10 km running performance. Eighteen male endurance runners performed: 1) an incremental test to exhaustion to determine VO_{2max} and PTV; 2) a constant submaximal run at 12 km·h^{-1} on an outdoor track for RE determination; and 3) a 10 km running race. Unadjusted (VO_{2max}, PTV and RE) and adjusted variables ($VO_{2max}{}^{0.72}$, $PTV^{0.72}$ and $RE^{0.60}$) were investigated through independent multiple regression models to predict 10 km running race time. There were no significant correlations between 10 km running time and either the adjusted or unadjusted VO_{2max}. Significant correlations ($p < 0.01$) were found between 10 km running time and adjusted and unadjusted RE and PTV, providing models with effect size > 0.84 and power > 0.88. The allometrically adjusted predictive model was composed of $PTV^{0.72}$ and $RE^{0.60}$ and explained 83% of the variance in 10 km running time with a standard error of the estimate (SEE) of 1.5 min. The unadjusted model composed of a single PVT accounted for 72% of the variance in 10 km running time (SEE of 1.9 min). Both regression models provided powerful estimates of 10 km running time; however, the unadjusted PTV may provide an uncomplicated estimation.

Key words: *VO_{2max}; peak of treadmill velocity; running economy; allometry.*

Introduction

Endurance performance has been associated with the capacity for oxygen uptake (VO_2). As a consequence, maximal oxygen uptake (VO_{2max}) has traditionally been considered as a key variable when either prescribing training for competitive middle and long distance runners (Brandon and Boileau, 1987; Pollock, 1977), or for predicting performance in prolonged events (Midgley et al., 2006). However, the predictive power of VO_{2max} has been challenged as some studies reported low correlations between VO_{2max} and endurance performance in trained and untrained individuals (Conley and Krahenbuhl, 1980; Noakes et al., 1990; Stratton et al., 2009). A factor which may be related to poor predictive power of VO_{2max} is the difference in body dimensions (Chamari et al., 2005; Eisenmann et al., 2001; Vanderburgh and Laubach, 2008), as studies have often not considered variations in body mass when measuring VO_{2max}.

Other physiological variables, such as running economy (RE), defined as the energy

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demand for a given velocity of submaximal running (Saunders et al., 2004), has been associated with endurance running performance (Conley and Krahenbuhl, 1980). For example, RE predicts aerobic training effects and endurance performance in highly trained runners with comparable VO_{2max} values (Conley and Krahenbuhl, 1980). Furthermore, RE was able to detect lower changes caused by a physical training program in well trained athletes with similar VO_{2max} values (Saunders et al., 2004). However, some studies have also found low correlations between RE and endurance performance, making the predictive power of RE poor in untrained individuals (Stratton et al., 2009; Tolfrey et al., 2009). As RE is also influenced by variations in body mass, a possible explanation for the poor predictive power between RE and endurance performance may be the lack of allometric adjustment in submaximal VO_2 values (Berg, 2003).

In addition to VO_{2max} and RE, the peak treadmill running velocity (PTV), defined as the fastest speed attained and maintained for one minute in a VO_{2max} test, is also a potential predictor of endurance performance. For example, PTV predicted performance of runners in races of different distances (r = -0.88 to -0.94 in races of 10-90 km) (Noakes et al., 1990), as well as of an Olympic-distance National Triathlon Championship (1500 m swim, 40 km cycle, 10 km run) (r = 0.85) (Schabort et al., 2000). However, Legaz-Arrese et al. (2011) challenged the usefulness of the PTV to discriminate endurance performance in elite runners, as steeplechase elite runners elicited greater PTV when compared to elite marathon runners. This result contradicts the suggestion that the higher the PTV the better the endurance performance. In accordance with maximal aerobic power and RE, these results also suggest that differences in body mass may affect the PTV, as steeplechase runners were heavier than the marathoners (McLaughlin et al., 2010).

A common factor that may have affected the predictive power of VO_{2max}, RE and PTV in those studies was the lack of allometric correction according to variations in body mass (Conley and Krahenbuhl, 1980; Legaz-Arrese et al., 2011; Noakes et al., 1990; Stratton et al., 2009). Given the non-linear relationship between body size and a metabolic rate, some studies have used allometric scaling of body mass to improve the predictive power of maximal and submaximal VO_2 values (Agutter and Wheatley, 2004; Bergh et al., 1991; McLaughlin et al., 2010). Therefore, the lack of allometric scaling may have biased results of those studies, decreasing the power of VO_{2max}, RE and PTV in predicting endurance performance. The laws of proportionalities and scaling support the notion that VO_2 values are proportional to body mass raised to the power between 0.60 and 0.75 (Chamari et al., 2005; Eisenmann et al., 2001; Vanderburgh and Laubach, 2008). Furthermore, others have also suggested allometric scaling on mechanical variables when predicting performance (Crewther et al., 2011; Vanderburgh and Laubach, 2008). For example, a greater predictive power of cycling endurance performance was found when the peak power output determined in a preliminary VO_{2max} test was corrected by an allometric exponent (Lamberts et al., 2012). However, no study has yet verified whether running endurance performance is better predicted by PTV values after allometric adjustments for body mass.

Despite the controversy, the prediction of running endurance performance by VO_{2max} test variable(s) still remains as current debate, and recent studies have investigated the correlations between VO_{2max} test outputs and middle and long-distance running performance (Legaz-Arrese et al., 2011; McLaughlin et al., 2010; Stratton et al., 2009). For example, McLaughlin et al. (2010) submitted 17 runners to a VO_{2max} test, and using a stepwise regression model they found that the velocity at VO_{2max} was the best predictor of a 16 km running time trial. However, this study only analyzed unadjusted variables so it was not determined whether allometrically adjusted VO_{2max} and RE, together with the PTV, would have improved the endurance performance prediction.

Therefore, the objective of this study was to develop a multiple regression model derived from allometrically adjusted VO_{2max}, RE and PTV to determine whether the model would predict endurance performance with greater accuracy than the existing predictions. Considering that VO_{2max}, RE and PTV without allometric adjustments had been used to predict endurance performance with varying degrees of accuracy, we hypothesized that these variables would improve the endurance performance prediction when adjusted by allometric scaling. A 10 km running race was selected as the performance measure taking into account that this is a race distance that several long distance runners (5 km, 10 km, half-marathon, marathon, ultra-marathon and cross-country runners) compete in.

Material and Methods

Participants

Eighteen male endurance runners (29.1 ± 5.1 years old, 66.9 ± 10.3 kg and 173.9 ± 7.30 cm) volunteered to participate in the study. After explanation of all experimental procedures, possible risks and benefits, each runner gave his written informed consent. They were regional competitive runners with an uninterrupted training experience of $\geq$ 3 years, best 10 km running time $\leq$ 40 min and weekly training frequency of $\geq$ 3 sessions. The study was approved by the Ethics Committee of the University of São Paulo, which conformed to the Declaration of Helsinki.

Procedures

Runners visited the laboratory on three different occasions, separated by at least 48 h, within a 14 day period. Each runner completed: 1) a laboratory maximal incremental test to exhaustion on a treadmill for the determination of VO_{2max} and PTV; 2) a 12 $km{\cdot}h^{-1}$ constant running test on an outdoor track for RE determination; and 3) a 10 km running race completed as a competitive simulation on the outdoor track to determine the endurance running performance. Subjects were asked to avoid intense training during the 24 h before the procedures, and maintain a habitual diet and training for the duration of the study. All tests were performed at the same time of the day. The tests performed on the outdoor track had windless conditions, 60% air humidity and temperature ranging from 19 to 22°C.

Maximal Incremental Test on a Treadmill

After a 3 min warm-up walking at 6 $km{\cdot}h^{-1}$, the test was immediately started with 1.2 $km{\cdot}h^{-1}$ increases every 3 min until volitional exhaustion. The treadmill gradient was maintained at 1% elevation, thus simulating the outdoor running energy cost (Jones and Doust, 1996). Verbal encouragement was provided throughout the test to ensure the attainment of maximal effort, and the exhaustion was identified when runners were not able to maintain the running pace. Individuals wore a mask (Hans Rudolph®, Kansas City, MO, USA) throughout the test to measure the pulmonary VO_2. VO_2 was recorded breath-by-breath with a gas analyzer (K4b^2, Cosmed, Italy), previously calibrated according to the manufacturer's instructions. Briefly, O_2 and CO_2 sensors were calibrated using ambient air and a known composition gas (12% O_2 and 5% CO_2), while the turbine flowmeter was calibrated using a 3-L syringe (Quinton Instruments, USA). Thereafter, breath-by-breath VO_2 data were converted to 10 s averages. Similarly to previous research (Ingham et al., 2008; Weston et al., 2002), VO_{2max} was defined as the highest value reached for 30 s during the last stage of the incremental test. Furthermore, the highest velocity attained during the last stage fully completed was recorded as PTV.

Running Economy Test

Runners performed an individual 10 min warm-up composed of stretching and low intensity running. Thereafter they performed a 6 min running bout at 12 $km{\cdot}h^{-1}$ on a 400 m outdoor track, while the pulmonary VO_2 was taken breath-by-breath (K4b^2, Cosmed, Italy). As part of their training they used to run on an outdoor track at similar velocities, so that we hypothesized that improved RE may be found during RE tests performed on outdoor tracks. The 12 $km{\cdot}h^{-1}$ velocity was controlled by an evaluator and represented an intensity which was under the lactate threshold velocity for all the runners in the study. In previous analyses using velocities from 9 to 15 $km{\cdot}h^{-1}$, we verified that RE obtained at 12 $km{\cdot}h^{-1}$ presented the highest correlation with endurance performance indices ($r = 0.92$; $p < 0.01$), when compared to RE obtained at other velocities (Lima-Silva et al., 2010). The gas analyzer was calibrated before every test as described for the laboratory test. After converting breath-by-breath VO_2 measures to 10 s averages, RE was determined as the mean VO_2 response during the last 30 s of the 12 $km{\cdot}h^{-1}$ running bout.

10 km Running Race

After a self-paced warm-up, runners completed a 10 km running race on an outdoor 400 m track. To avoid alterations in performance as a consequence of different pacing strategies influenced by other runners, each runner completed the 10 km distance alone. The participants were asked to complete the 10 km as if it was a competition – the difference being that there was no feedback based on elapsed time or the heart rate (HR). They were verbally encouraged throughout the race. The time to complete the 10 km running race was measured manually by a digital chronometer.

Statistical Analyses

After determination of VO_{2max}, PTV and RE, as described in the former sections, these variables were allometrically adjusted based on exponents previously documented (Chamari et al., 2005; Eisenmann et al., 2001; Markovic et al., 2007), as a large sample size was not available in the present study. Thus, a number of exponents ranging from 0.60 to 0.75 were tested before the identification of exponents that provided the highest correlation with the dependent variable (i.e. running time). Following this, a 0.60 exponent was used on RE data ($RE^{0.60}$, expressed in $ml/kg^{0.60}/min$), while a 0.72 exponent was used to correct VO_{2max} ($VO_{2max}{}^{0.72}$, expressed in $ml/kg^{0.72}/min$) and PTV data ($PTV^{0.72}$, expressed in $km/h/kg^{0.72}$). Although a theoretical 0.66 exponent had been suggested for VO_{2max} values (Vanderburgh and Laubach, 2008), previous studies reported different empirical exponents ranging from 0.60 to 0.75 (Chamari et al., 2005; Eisenmann et al., 2001; Markovic et al., 2007). Furthermore, we used a 0.72 exponent for PVT as no correction had been reported for this variable (the rationale was that PTV is a maximal variable associated with VO_{2max} values).

Both groups of variables, unadjusted and adjusted by allometric exponents, were used separately to obtain two different multiple linear regression models. The Gaussian distribution was initially verified by the Shapiro-Wilk test, and a normal distribution was ensured for all independent and dependent variables. Multiple regression models based on unadjusted variables (without allometric correction) and adjusted variables (body mass scaled by 0.60 for RE and 0.72 for VO_{2max} and PVT) were obtained separately to predict the time to complete the 10 km run.

The Pearson's correlation coefficient was used to verify which variable(s) would be initially considered in these regression models. Based on partial correlations, collinearity and variance inflation factor principles, multiple stepwise regressions selected the group of independent(s) variable(s) which accounted for the greatest variation in the dependent variable and provided the lowest standard error of estimate (SEE) (Hair et al., 2009). Whilst VO_{2max}, RE and PTV, unadjusted and adjusted by allometric exponents, were independent variables, time to complete 10 km running was the dependent variable. In all analyses the statistical significance was set at 5% ($p < 0.05$) and final predictive models were accepted only if power and effect size (ES) were ≥ 0.80. The ES, expressed as the Pearson's correlation coefficient, was interpreted as small ($r \leq 0.20$), moderate ($0.21 > r < 0.79$) and large ($r \geq 0.80$) (Cohen, 1988).

Results

Runners completed the 10 km running race within 37.8 min (± 3.4), with mean velocity of 16.0 $km \cdot h^{-1}$ (± 1.4). Table 1 presents values of VO_{2max}, RE and PTV variables, unadjusted and adjusted by allometric exponents.

There were no significant correlations between the time to complete the 10 km running race and VO_{2max}, either adjusted or unadjusted by the 0.72 exponent. Therefore, VO_{2max} did not contribute to the initial regression stepwise models. In contrast, significant correlations were observed between the time to complete the 10 km run and RE and PTV, either unadjusted or adjusted by 0.60 and 0.72 allometric exponents, respectively (Table 2). Thus, these variables were utilized in the initial predictive models of 10 km running performance.

Adjusted and unadjusted final multiple stepwise regression models were obtained with large effect size from 0.84 to 0.94 (expressed as the Pearson's coefficient) and power ranging from 0.88 to 0.99. When using variables without allometric scaling, the final predictive model was obtained by inserting PTV as the single best predictor so that a model with PTV accounted for 72% of the variance in the time to complete the 10 km running race. When SEE was expressed relative to the mean time to complete 10 km running, the predictive model obtained with the single PTV produced a SEE of 4.9% (1.9 min).

Analysis with allometrically adjusted variables showed that both the PTV and RE ($PTV^{0.72}$ and $RE^{0.60}$) were inserted into the final stepwise predictive model. This adjusted final predictive model accounted for 83% of the variance in the time to complete the 10 km run, with a SEE of 4.0% (1.5 min). Table 3 presents the coefficients obtained in both unadjusted and adjusted final multiple regression models.

Table 1

Values of VO_{2max}, RE and PTV, adjusted and unadjusted by allometric exponents.

	Mean (± SD)	Minimum	Maximum	95% CI
VO_{2max} (ml/kg/min)	62.5 ± 7.0	47.9	77.9	59.3 - 65.6
$VO_{2max}^{0.72}$ (ml/kg$^{0.72}$/min)	156.8 ± 17.3	132.9	182.1	149.0 - 163.8
RE (ml/kg/min)	2648.2 ± 573.9	1847.0	4003.0	2390.1 - 2906.3
$RE^{0.60}$ (ml/kg$^{0.60}$/min)	107.3 ± 51.6	157.7	111.0	102.8 - 115.0
PVT (km/h)	17.3 ± 0.9	15.1	18.0	16.8 - 17.7
PVT (km/kg$^{0.72}$/h)	0.9 ± 0.1	1.0	0.6	0.8 – 0.9

 # VO_{2max} - maximal oxygen uptake; RE - running economy; PTV - peak treadmill running velocity; CI - 95% confidence interval

Table 2

Correlation coefficients between time to complete the 10 km run and variables with or without allometric correction.

	VO_{2max} (ml/kg/min)	RE (ml/kg/min)	PTV (km/h)	VO_{2max} (ml/kg$^{0.72}$/min)	RE (ml/kg$^{0.60}$/min)	PTV (km/ kg$^{0.72}$/h)
10 km run (min)	-0.33	0.67[b]	-0.85[b]	-0.47	0.74[b]	-0.66[b]
VO_{2max} (ml/kg/min)	1	-0.42	0.42	0.86[b]	-0.38	0.41
RE (ml/kg/min)		1	-0.66[b]	-0.75[b]	0.90[b]	-0.89[b]
PTV (km/h)			1	0.58[a]	-0.57[a]	0.81[b]
VO_{2max} (ml/kg$^{0.72}$/min)				1	-0.58[b]	0.79[a]
RE (ml/kg$^{0.60}$/min)					1	-0.66[b]

 # 10 km run - time to complete the 10 km run; VO_{2max} maximal oxygen uptake; RE - running economy; PTV is peak treadmill running velocity. Significant correlations were reported as letters a ($p < 0.05$) and b ($p < 0.01$).

Table 3

Final multiple stepwise regression models of the predicted time to complete the 10 km run

Regression Model	Predictive Variables	R^2	SEE	bSTD	Power	ES	*p*
Unadjusted	PTV	0.72	1.9	-0.85	0.88	0.94	< 0.001
Adjusted	$PTV^{0,72}$ + $RE^{0,60}$	0.83	1.5	-0.64 + 0.39	0.99	0.84	< 0.01

 # SEE - standard error of the estimate; bSTD - beta standardized coefficient; ES - effect size of the model; PTV - peak treadmill running velocity; RE - running economy.

Discussion

Traditional aerobic indexes such as VO_{2max}, RE and PTV have been used to predict endurance performance with varying degrees of accuracy. Thus, we verified if a multiple regression model derived from these indexes, allometrically adjusted, may predict endurance performance with greater accuracy. The first finding of this study was that a model incorporating $PTV^{0.72}$ and $RE^{0.60}$ accounted for 83% of the variance in the time to complete the 10 km running race. The second finding was that a single unadjusted PTV also provided a powerful (reliable with low error of estimation) estimation of 10 km running performance, accounting for 72% of the variance in the time to complete the 10 km run. The large effect size (0.84 to 0.94) and power (0.88 to 0.99) indicate the power of the final stepwise regression models. These results have important practical implications, as they show that a traditional test used to assess variables associated with middle and long-distance running performance is able to provide reasonable estimation of a 10 km running performance.

To the best of our knowledge, only the study by Ingham et al. (2008) investigated variables allometrically adjusted to predict running performance. Given the methodological differences regarding dependent and independent variables, allometric exponents and the aerobic profile of the runners, direct comparisons between both studies are difficult. For example, Ingham et al. (2008) found that a model based on VO_{2max} and RE variables, corrected with a 0.35 exponent, accounted for 96% of the variance in running velocity in a 800 m and 1500 m running race. In their analysis, Ingham et al. (2008) observed that the maximal aerobic velocity, the velocity corresponding to VO_{2max} (vVO_{2max}), did not improve the final predictive models. In contrast, our final adjusted regression model was composed of PTV and RE, without VO_{2max}. What was also different to Ingham et al. (2008), who calculated the vVO_{2max} by extrapolation from submaximal intensities, was that we used the actual measured PTV as maximal aerobic velocity. In addition, we used the time to complete a longer event, a 10 km running race as a dependent variable, while they used the mean velocity in 800 m and 1500 m running. These aspects may have had a different effect on the correlations between dependent and independent variables, leading to different predictive models in these studies (which may also explain the absence of correlation to VO_{2max}).

Another relevant aspect was the allometric correction, as Ingham et al. (2008) found a curvilinear relationship between dependent (i.e. running speed) and independent (i.e. VO_{2max} and RE) predictor variables such that VO_{2max} and RE values were corrected by a 0.35 exponent. Divergent to this, we found that exponents of 0.60 and 0.72 provided the best correction for RE and VO_{2max}, respectively. It is important to point out that previous studies reported different exponents around a 0.66 proportion (Chamari et al., 2005; Eisenmann et al., 2001; Vanderburgh and Laubach, 2008), when correcting maximal and submaximal VO_2 values of individuals with a similar profile. Therefore, because our sample size was not large enough to allow performing cross-validation regression diagnostics, we used this range of exponents to identify the best allometric adjustment. This approach is suggested when the simple size is limited (Hair et al., 2009; Zoeller et al., 2007).

Studies that have investigated how indices derived from VO_{2max} tests could predict running performance showed that unadjusted variables such as VO_{2max}, RE, $\%VO_{2max}$ at the lactate threshold and vVO_{2max} were strongly correlated with performance in 2 mile treadmill running ($R^2 = 0.69$ to 0.87) (Tolfrey et al., 2009) and a 16 km running race ($R^2 = 0.66$ to 0.94) (McLaughlin et al., 2010). However, when conducting a multiple stepwise regression model, McLaughlin et al. (2010) verified that a model that combined only unadjusted VO_{2max} and RE values best predicted the 16 km running performance. In that study, the inclusion of PTV did not improve the variance in performance accounted for by the model that included VO_{2max} and RE (97.3%). In contrast, the PTV was included in our final predictive adjusted model.

In the present study, the best multiple stepwise regression model obtained with a single PTV accounted for 72% of the variance in 10 km running time. This final predictive model was based on strict principles of partial correlation, collinearity, and a variance inflation factor (Hair et al., 2009). In accordance, each independent variable that accounted for equal variance in the dependent variable, having controlled the effect of other independent variables, was excluded. Thus, rather than considering the *F* probability as a single criterion to include variables, independent variables were inserted into the final stepwise regression model only when accounting for a new portion of the variance of the dependent variable. Due to high collinearity as well as a high variance inflation factor with PTV and a low partial correlation with performance, RE was not inserted into the final stepwise model with unadjusted data. Consequently, only the unadjusted PTV predicted the 10 km running performance.

Similar to our results, Stratton et al. (2009) reported that PTV was the single best predictor of a 5000 m running performance in individuals with different conditioning states. Neither VO_{2max} nor RE was added into a stepwise regression model in that study. Together, these and other results may suggest that PTV may be considered as a good global predictor of running performance in distances from 5 to 90 km. Perhaps the fact that PTV is related to maximal aerobic power, the anaerobic metabolism, neuromuscular factors and motivation (Noakes et al., 1990; Stratton et al., 2009) may explain the ability of the PTV to predict endurance running performance.

Our results have practical implications. Due to the simple and uncomplicated calculations, the predictive model obtained with a single PTV may be preferable when compared to the allometric adjusted model. In fact, a model composed of PTV and RE allometrically adjusted ($PTV^{0.72}$ and $RE^{0.60}$, respectively) would demand submaximal and maximal incremental tests to improve the estimates of the 10 km running performance by only 0.9%. In contrast, a single VO_{2max} incremental test may be feasible as this could provide a reliable estimation of endurance performance through a single PTV. Although one could argue that a 10 km running time trial is more specific than a VO_{2max} test when estimating running performance, it is important to note that VO_{2max} tests are traditionally used to assess physiological indices of fitness evaluation and endurance training prescription. Thus, indices such as VO_{2max} and aerobic/anaerobic thresholds, often used to determine different training zones (Legaz-Arrese et al., 2011), may be obtained together with a 10 km running performance estimate through a single test. Furthermore, a VO_{2max} test may be feasible, as this can be performed regardless of variations in environment conditions, such as weather and terrain.

Conclusion

A multiple regression model obtained with PTV and RE, but not VO_{2max}, provided powerful estimates of 10 km running performance when these variables were allometrically adjusted by 0.72 and 0.60 exponents, respectively. However, our results also showed that a single unadjusted PTV may provide a reasonable and uncomplicated estimate of endurance performance in long-distance runners, thus making the allometric adjustment unnecessary in practical terms.

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