Original Article

Allometric scaling of body mass in running economy data: An important consideration in modeling marathon performance

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ABSTRACT

The purpose of this study was to compare metabolic variables during submaximal running as predictors of marathon performance. Running economy (RE) and respiratory exchange ratio (RER) data were gathered during a 30 min incremental treadmill run completed within 2 weeks prior to running a 42.2-km marathon. Paces during the treadmill run progressed every 5 min from 75-100% of 10-km race velocity. Variables at each stage were analyzed as predictors of relative marathon performance (RMP) in competitive (COMP) and recreational (REC) runners. Twenty-nine runners were classified as COMP (n = 12; age 30 ± 8 years) or REC (n =17; age 20 ± 1 year) based on performance in shorter races. RMP was calculated as percent difference from predicted marathon finish time. Two methods of calculating RE were used: unscaled ($ml \cdot kg^{-1} \cdot km^{-1}$) and with allometric scaling of body mass ($ml \cdot kg^{-0.75} \cdot km^{-1}$). The COMP runners were significantly more economical than REC (p=0.005; p=0.015 with scaling). For the whole population, RE with and without scaling was significantly correlated with RMP. Within groups, RMP was not significantly correlated with RE unless scaling was used: COMP runners at 75% (p=0.044), 80% (p=0.040), and REC runners at 85% (p=0.038). Runners classified as COMP were more economical than REC, but RER was not different. The use of allometric scaling is important when assessing homogeneous groups. In this study, allometrically-scaled RE at 80-85% of 10-km velocity was the best predictor of RMP within groups. **Key words:** DISTANCE RUNNING, RESPIRATORY EXCHANGE RATIO, ENDURANCE TRAINING, OXYGEN KINETICS, EXERCISE EFFICIENCY

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INTRODUCTION

Running economy (RE) has been characterized as an important factor in determining distance running performance (Barnes and Kilding, 2015; Foster and Lucia, 2007; Joyner and Coyle, 2008; Saunders et al., 2004b), and it appears that RE can be improved with distance running in a recreational population (Beneke and Hutler, 2005). Running economy is quantified as the oxygen cost of running at a submaximal pace (Saunders et al., 2004b). An individual's RE is typically assessed using treadmill testing and a metabolic cart to measure oxygen utilization, and is expressed as VO_2 (in $mL \cdot kg^{-1} \cdot min^{-1}$) at a specified sub-maximal pace or paces. An alternative approach to assessing RE at a specific pace is to express RE relative to distance covered $m \cdot mL^{-1} \cdot kg^{-1}$ (Turner et al., 2003) or in $mL \cdot kg^{-1} \cdot km^{-1}$ (Foster and Lucia, 2007), which allows for comparison of economy at different velocities. While reporting RE per kg of body mass is common, previous work indicates that the relationship between body mass and oxygen cost do not increase proportionately, and thus body mass should be scaled allometrically, raising body mass to a power of between 0.66 and 0.75 (Berg, 2003; Bergh et al., 1991; Helgerud, 1994; Saunders et al., 2004b; Storen, et al., 2011; Svedenhag, 1995). The evidence in support of using allometric scaling of body mass in running economy data appears strong, having emerged from several lines of research (Svedenhag, 1995). Despite this, data are often reported without scaling. It is unknown whether this is due to lack of knowledge, tradition, the relative lack of normative data, or simply to avoid the required additional calculations.

Running economy studies have high test-retest reliability (1.5-5.0%) among a range of populations (Armstrong and Costill, 1985; Pereira and Freedson, 1997; Saunders et al., 2004a). Typical error can be reduced by ensuring that proper controls are taken to standardize time of testing, testing equipment, nutritional status, recent training, environmental conditions, footwear, and other potential confounding variables (Pereira and Freedson, 1997; Saunders et al., 2004a).

Metabolic adaptations have been identified as critical contributors to marathon running performance (Hawley and Spargo, 2007). As exercise intensity increases, a shift away from fat and toward carbohydrate utilization occurs (Coyle, 1995). Respiratory exchange ratio (RER), defined as $VCO_2 \cdot VO_2^{-1}$, provides a non-invasive, reliable measure of substrate metabolism (ratio of fat to carbohydrate utilization) during low to moderate intensity exercise (Jeukendrup and Wallis, 2005). Mitochondrial adaptations to endurance training enhance the capacity for fat metabolism, which, in turn, spares glycogen for use later in a long exercise bout such as a marathon (Hawley and Spargo, 2007). Some researchers have suggested that energy cost, which incorporates metabolic substrate (usually measured with RER), provides a more sensitive measure of exercise economy than oxygen cost (Shaw et al., 2013; Fletcher et al., 2009). Prolonged, intense endurance training leads to an increased capacity to utilize fat as fuel during exercise (Coyle, 2007; Hawley, 2002; Hawley and Spargo, 2007). This decreased reliance on glycogen stores may be a particularly important factor in events like the marathon, where glycogen depletion can be a limiting factor to performance (Coyle, 2007; Hawley and Spargo, 2007).

A more economical runner can do the same amount of work with less energy utilization, and thus less fatigue, making RE an important aspect of distance running performance (Joyner and Coyle, 2008; Saunders et al., 2004b). The aim of this study was to compare RE with and without allometric scaling, and RER as predictors of marathon performance. Differences between competitive (COMP) and recreational (REC) runners were analyzed, as were factors within groups. Variables of interest were used to model relative marathon performance (RMP) as percent difference from predicted finish time, for the whole population and by group. The research hypothesis was that RE utilizing allometric scaling would be the strongest predictor of RMP, with more economical runners attaining times closer to their predicted marathon finish times.

MATERIALS AND METHODS

Design

This study utilized a cross-sectional design, with a dependent variable of RMP, calculated as percent difference from predicted marathon finish time, which was based on a recent race or time trial of between 2-mi and 10-km. The independent variables assessed were RE with and without allometric scaling and RER during a continuous, six-stage, incremental, sub-maximal 30 min treadmill run, beginning at 75% of 10-km race velocity and finishing at 100% of 10-km velocity. This protocol was developed in order to assess an RE profile over a range of velocities, based on the work of Daniels and Daniels (1992), who showed that RE is dependent upon velocity and should be assessed at up to 90% of VO_{2MAX}. Running economy was calculated as the average O_2 during each 5 min stage in $mL \cdot kg^{-1} \cdot km^{-1}$, and with allometric scaling, in $mL \cdot kg^{-0.75} \cdot km^{-1}$, with the scaling exponent chosen based on the recommendation of Bergh et al. (1991).

Subjects

Subjects were recruited from a marathon training class, local running clubs, and running distribution lists. Prior to enrollment, a consent form was provided for review. Researchers explained the nature of the study and associated risks. Consent was obtained in person prior to any testing. All procedures and protocols were approved by the University Institutional Review Board.

Enrollment in the study required completion of a time trial or road race of between 2-mi and 10-km in the two months prior to running a 42.2-km road marathon, as well as a lab visit to complete the 30 min submaximal treadmill run. Exclusion criteria included any health condition that would contra-indicate a 30 minute run of moderately challenging nature on the treadmill, or the inability to complete the run without a maximal effort. Four enrolled subjects failed to complete the treadmill run without a maximal effort as indicated either by volitional exhaustion that led to the premature cessation of the run, or by a plateau and subsequent drop in oxygen use, accompanied by an RER of higher than 1.10.

Subjects were stratified by group as COMP or REC, with a predicted Boston Marathon qualifying (3:05 for men and 3:35 for women) time set as the cut-off. This allowed for assessment of differences between the groups in RE and RER at a range of submaximal intensities, and for linear regression modelling to predict RMP for the whole population (ALL) as well as by group. Subject characteristics are shown in Table 1. The COMP group was older, ran faster in the marathon, and finished closer to their predicted marathon time.

Procedures

Subjects ran on a motorized Woodway Pro XL 27 treadmill (Waukesha, WI) for a total of 33 min, including a 3 min warm-up and 6 stages of 5 min each. They were advised to refrain from strenuous activity for 48 hours prior to testing, and to follow a dietary regiment similar to that which they typically use prior to a race or challenging workout. Stages were calculated from a recent race performance, ranging in distance from 2-mi up to 10-km. Recent race times from distances other than 10-km were converted to a 10-km race equivalent using commonly utilized race pace conversion charts (Daniels, 2013). The warm-up was done at 70% of 10-km velocity, and the subsequent stages were at 75%, 80%, 85%, 90%, 95%, and 100% of 10-km velocity. A face mask and flow sensor were worn for gas analysis via a Medgraphics Ultima series metabolic cart (MGC Diagnostics, St. Paul, MN, USA). Standard calibration procedures of the metabolic cart were used prior to each testing session.

Height and weight were measured prior to the treadmill test. Subjects removed footwear, and height was measured to the nearest ¼ inch using an Accustat Genentech Stadiometer (San Francisco, CA). Weight was measured in pounds to the nearest tenth using a ProDoc Detecto (PD300) scale (Webb City, MO), then converted to kilograms. During weighing, subjects wore light, minimal clothing, such as running shorts or half-tights and a jog-bra (women).

Data analysis

In order to assess metabolic response to exercise of moderate duration over a range of sub-maximal paces, a number of factors were assessed at each of the 6 stages, and as averages over the entirety of the 30 min test. Running economy was assessed and reported with and without allometric scaling for the full 30 min and for each of the stages, with the average value across the 5 min stage reported. In accordance with previous recommendations, we selected a scaling exponent of 0.75 for body mass (Bergh et al., 1991; Svedenhag, 1995). Respiratory exchange ratio was assessed and reported as the average value for each of the 6 stages as well as the 30 min average.

Predicted marathon finish time was calculated from the shorter race or time trial using commonly utilized race pace conversion charts (Daniels, 2013). Chip times were used for marathon finish times, and times were confirmed with subject via phone or email. Percent difference from expected finish time was then calculated and reported as the relative marathon performance (RMP) variable. A positive percent indicates a slower than predicted marathon finish time, while a negative percent indicates a faster than predicted marathon time.

Statistical Analysis

Means and standard deviations for all subjects and the two groups were calculated. Subject characteristics for the two groups were assessed using independent samples *t* tests. All data were tested for normality and homoscedasticity using the Shapiro-Wilk and Levene tests. Comparisons between the groups were done to assess differences between COMP and REC runners, using independent samples *t* tests, or with non-parametric tests in a few cases where the assumption of normality was not met. Significance for all tests was set at $p \leq 0.05$.

Running economy and RER variables at each stage and for the 30 min average were assessed for correlations with RMP using Pearson's *r*, and multiple linear regression modeling was performed for ALL, COMP and REC runners. Stepwise regression was done with $p \leq 0.05$ set as the threshold. Regressions were performed for ALL, COMP, and REC runners to assess whether different factors are more important in predicting RMP in these two populations and the combined cohort. Statistical analysis was done using SPSS, Version 21 (IBM Corp., Armonk, NY).

RESULTS

For the 30 min average, COMP runners were significantly more economical than REC both without and with allometric scaling ($p = 0.005$; $p = 0.018$). Average velocity during the 30 min run was significantly faster for COMP than REC runners (13.8 vs. 11.1 $km \cdot h^{-1}$; $p \leq 0.001$). Averages across the 30 min run are reported in Table 1. Stage-by-stage statistics reflect the same patterns (See Supplemental Digital Table 1). No differences were found between the groups in the RER data.

Pearson's *r* correlations between RMP and the 30 min average for the unscaled RE, scaled RE and RER are shown in Table 2**.** Correlations and *p*-values are reported for ALL, COMP, and REC. For stage-by-stage correlations and *p*-values see Supplemental Digital Table 2.

Table 1. Anthropometric, Performance, and RE Characteristics of COMP and REC runners.

Group	**ALL**	**COMP**	**REC**	***p***
Age	24 ± 7	30 ± 8†	20 ± 1	0.002
MT (min)	225.1 ± 51.2	178.1 ± 12.5†	258.2 ± 40.7	≤ 0.001
RMP	9.9 ± 8.6	1.7 ± 3.2†	15.7 ± 5.8	≤0.001
V ($km \cdot h^{-1}$)	12.2 ± 1.8	13.8 ± 0.8†	11.1 ± 1.4	≤ 0.001
Unscaled RE ($mL \cdot kg^{-1} \cdot min^{-1}$)	204.6 ± 16.7	194.7 ± 9.8†	211.6 ± 17.3	0.005
Scaled RE ($mL \cdot kg^{-0.75} \cdot min^{-1}$)	586.8 ± 49.0	561.8 ± 35.3†	604.4 ± 50.5	0.018
RER	0.99 ± 0.06	0.98 ± 0.05	1.00 ± 0.07	0.496

All results are ± S.D.
MT = marathon finish time.
RMP = % difference from predicted marathon finish time.
The rest of the variables are the results of the RE test, reported as averages across the 30 minutes.
p values are two-tailed.
†Significantly different from REC group at $P \leq 0.05$.

Table 2. Correlations with RMP

Variable	Group	*r*	*p*
Unscaled RE	ALL	0.619†	.000
	COMP	0.386	.215
	REC	0.419	.094
Scaled RE	ALL	0.611†	.000
	COMP	0.555	.061
	REC	0.479	.052
RER	ALL	0.127	.512
	COMP	0.249	.436
	REC	-0.019	.942

†Significantly correlated at $p \leq 0.05$

Running economy with and without allometric scaling was significantly related to RMP for ALL at all stages and for the 30 min average. The correlation was positive, with higher oxygen cost per km equating to a higher RMP (or a slower than expected time). For both groups, the trend for all of the stages and the 30 min average was in the same positive direction. Without allometric scaling, the REC runners showed a trend towards a relationship ($p = 0.068$ at 85% and $p = 0.094$ for the 30 min average), but there were no statistically significant correlations for REC or COMP.

When allometric scaling of BM was applied, statistically significant relationships were found within both the COMP and REC groups. While the 30 min average was not significantly related to RMP, a strong trend was observed in both groups ($p = 0.061$ for COMP and $p = 0.052$ for REC). Some stages were significantly correlated to RMP within groups: COMP runners: at 75% ($p = 0.044$) and 80% ($p = 0.040$), and REC runners at 85% ($p = 0.038$). Many other stages showed a trend of $p \leq 0.10$). No significant relationships were observed between RER and RMP for any of the stages or the 30 min average.

The multiple linear regression model to predict RMP for ALL runners included RE without scaling at 85% of 10k velocity and RER at 80% of 10-km velocity (R-sq = 0.530). The regression equation produced by this model was y = -126.49 + 0.382(RE without scaling @ 85%) + 59.41(RER @ 80%). For COMP runners the linear regression model included only RE with scaling at 80% of 10-km velocity (R-sq = 0.400). The regression equation for COMP runners was y = -27.11 + 0.051(RE with scaling @ 80%). For REC runners the linear regression model included only RE with scaling at 85% of 10-km velocity (R-sq = 0.256). The regression equation for REC runners was y = -19.01 + 0.057(RE with scaling @ 85%).

DISCUSSION

The findings of this study are that RE with allometric scaling of body mass produces a more sensitive model than RE without scaling as a predictor of RMP among COMP and REC runners, and that RER is not different between groups, nor is it a significant predictor of RMP within homogeneous groups.

A direct relationship was observed between RE and RMP, with higher oxygen cost per km associated with greater difference from predicted marathon finish time. Differences between COMP and REC runners were seen at all stages and for the 30 min average with and without allometric scaling. Stage-by-stage data with allometric scaling are shown in Figure 1.

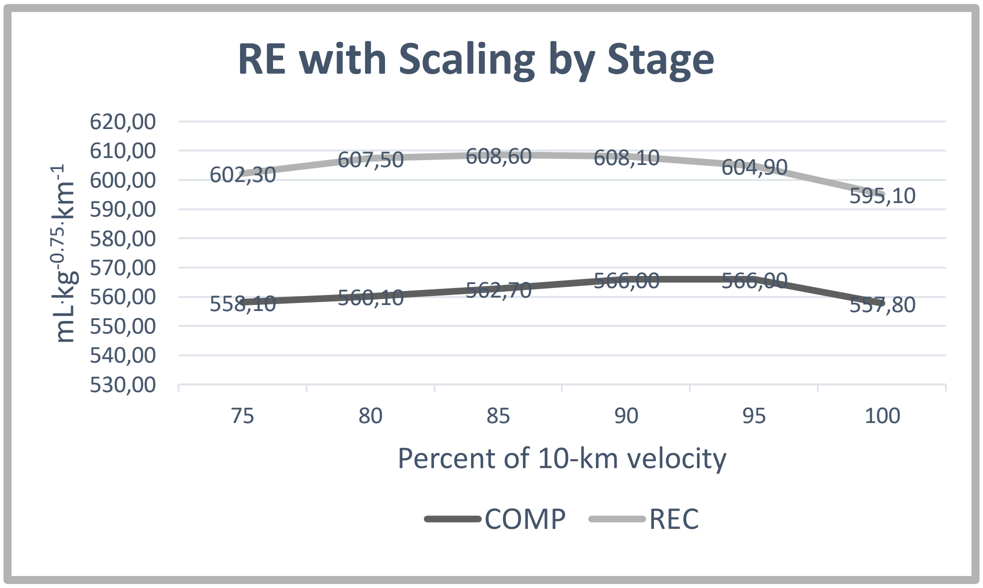

Figure 1. RE with allometric scaling of body mass by stage for COMP and REC runners

Unscaled RE significantly correlated with RMP for ALL runners, but not within REC or COMP groups. This is not entirely surprising in light of previous research on allometric scaling, which suggests that reporting O_2 utilization per kg is flawed due to the non-linear relationship between the cost of running and body weight (Berg, 2003; Bergh et al., 1991; Helgerud 1994, Svedenhag, 1995). Heavier runners have been reported to be more economical than light runners, as a result of reporting RE without allometric scaling, whereas lower BM has been identified as an important attribute in distance running performance (Bale et al., 1986; Mello et al., 1988; Sinnett et al., 2001).

Allometric scaling of RE appears to produce a more sensitive model of predicting relative marathon performance for homogeneous groups. Scaled RE at some of the stages was significantly related to RMP in

COMP (75 and 80% of 10-km velocity) and REC runners (85% of 10-km velocity), with other stages and averages across the 30-min approaching significance. Used in combination with races or time trials of shorter distance, scaled RE appears to be an important predictor of RMP.

The multiple linear regression models for COMP, REC, and ALL participants differed slightly. The selection of RE with scaling for both the COMP and REC runners may reflect the importance of utilizing allometric scaling in calculating RE. On the other hand, in ALL runners (a heterogeneous population), it appears that scaling may be less important, and that RER at 80% of 10-km velocity (a velocity near marathon pace) may be an important secondary factor in predicting marathon performance. The *r*-square values indicate that while RE factors can be used in predicting marathon performance, there are clearly other factors to consider in order to produce stronger predictive models.

This study is not without limitations. The authors acknowledge that the COMP and REC groups were not matched for age and sex, but were able to detect no differences within groups based on those characteristics. Further Helgerud (1994) found that when allometric scaling was used, women were more economical than men when matched for marathon finish time. In our study, there were proportionally more women in the REC and fewer in the COMP, but the REC group was still less economical. The recruitment of a larger sample size or a more elite population for the COMP group may have allowed for detecting significant differences in RER and possibly an association between RER and RMP. Further, the use of time trials and shorter distance races to set the velocities rather than VO_{2MAX} assumes that all participants exerted the same effort in their time trial or race, whereas competitive runners may push themselves nearer to the max of their physiological capabilities.

CONCLUSION

Runners classified as COMP were significantly more economical than their REC counterparts. The use of allometric scaling did not shed any additional light on the analysis for ALL runners, but improved RE as a predictor of RMP within both COMP and REC groups. There were no differences between the groups in RER, and RER was not significantly related to MP. However, RER during submaximal exercise may have a small but important impact on RMP particularly in heterogeneous groups.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Supplementary Table 1. Stage-by-Stage RE and RER for COMP and REC Runners

	RE (non-scaled)				**RE (scaled)**				**RER**			
%10-km	ALL	COMP	REC	Sig.	ALL	COMP	REC	Sig.	ALL	COMP	REC	Sig.
75	203.4 ± 18.2	193.2 ± 11.3†	210.5 ± 18.2	*p* = 0.009	584.0 ± 55.0	558.1 ± 44.8†	602.3 ± 55.4	*p* = 0.031	0.94 ± 0.05	0.93 ± 0.03	0.94 ± 0.07	*p* = 0.613
80	204.7 ± 17.7	193.8 ± 11.3†	212.4 ± 17.5	*p* = 0.003	587.9 ± 52.7	560.1 ± 40.9†	607.5 ± 52.3	*p* = 0.014	0.97 ± 0.06	0.97 ± 0.04	0.97 ± 0.07	*p* = 0.743
85	205.4 ± 17.0	194.9 ± 9.0†	212.8 ± 17.5	*p* = 0.003	589.6 ± 50.0	562.7 ± 33.4†	608.6 ± 51.8	*p* = 0.012	0.98 ± 0.06	0.98 ± 0.05	0.99 ± 0.07	*p* = 0.759
90	205.9 ± 16.8	196.0 ± 9.6†	212.8 ± 17.5	*p* = 0.005	590.7 ± 49.3	566.0 ± 35.0†	608.1 ± 51.3	*p* = 0.020	1.00 ± 0.06	0.99 ± 0.05	1.00 ± 0.07	*p* = 0.506
95	205.1 ± 16.1	196.0 ± 9.8†	211.5 ± 16.8	*p* = 0.005	588.8 ± 46.7	566.0 ± 33.1†	604.9 ± 48.9	*p* = 0.024	1.02 ± 0.07	1.01 ± 0.06	1.03 ± 0.08	*p* = 0.440
100	202.0 ± 18.0	193.2± 10.2†	208.2± 19.9	*p* = 0.025	579.7 ± 50.6	557.8.1 ± 32.2†	595.1 ± 56.2	*p* = 0.048	1.06 ± 0.09	1.04 ± 0.06	1.08 ± 0.10	*p* = 0.263
AVE	204.6 ± 16.7	194.7 ± 9.8†	211.6 ± 17.3	*p* = 0.005	586.8 ± 49.0	561.8 ± 35.3†	604.4 ± 50.5	*p* = 0.018	0.99 ± 0.06	0.98 ± 0.05	1.00 ± 0.07	*p* = 0.496

All results are ± S.D. *p*-values are two-tailed.†Significantly different from REC group at $P \leq 0.05$. %10-km = percent of 10-km velocity. RE = non-scaled values ($ml\cdot kg^{-1}\cdot km^{-1}$), RE scaled = allometrically scaled values ($ml\cdot kg^{-0.75}\cdot km^{-1}$). RER = VCO_2/VO_2.

Supplementary Table 2. Stage-by-Stage Correlations with Relative Marathon Performance

	RE (non-scaled)			**RE (scaled)**			**RER**		
%10-km	ALL	COMP	REC	ALL	COMP	REC	ALL	COMP	REC
75	0.606† (≤0.001)	0.482 (0.113)	0.420 (0.092)	0.580† (0.001)	0.588† (0.044)	0.454 (0.067)	0.111 (0.587)	0.103 (0.751)	0.043 (0.870)
80	0.646† (≤0.001)	0.504 (0.095)	0.426 (0.085)	0.623† (≤0.001)	0.598† (0.040)	0.473 (0.055)	0.078 (0.686)	0.117 (0.716)	0.029 (0.911)
85	0.652† (≤0.001)	0.419 (0.175)	0.453 (0.068)	0.640† (≤0.001)	0.569 (0.054)	0.506† (0.038)	0.069 (0.722)	0.181 (0.574)	-0.003 (0.991)
90	0.615† (≤0.001)	0.415 (0.180)	0.407 (0.105)	0.599† (0.001)	0.564 (0.056)	0.460 (0.063)	0.108 (0.576)	0.282 (0.375)	-0.071 (0.787)
95	0.584† (0.001)	0.239 (0.455)	0.406 (0.106)	0.586† (0.001)	0.453 (0.140)	0.463 (0.055)	0.141 (0.464)	0.296 (0.350)	-0.035 (0.895)
100	0.497† (0.006)	0.164 (0.610)	0.326 (0.201)	0.514† (0.004)	0.408 (0.188)	0.396 (0.115)	0.190 (0.323)	0.358 (0.254)	-0.049 (0.851)
AVE	0.619† (≤0.001)	0.386 (0.215)	0.419 (0.094)	0.611† (≤0.001)	0.555 (0.061)	0.479 (0.052)	0.127 (0.512)	0.249 (0.436)	-0.019 (0.942)

Correlations with RMP (% difference from expected marathon time). All results are Pearson's *r* (*p*-value) †Significantly correlated @ $p \le 0.05$. RE = non-scaled values (ml·kg^{-1}·km^{-1}), RE scaled = allometrically scaled values (ml·kg$^{-0.75}$·km^{-1}). RER = VCO_2/VO_2.