REVIEW

Running efficiency and long-distance performance prediction: Influence of allometric scaling

Efficience métabolique et prédiction de la performance en course à pied de longue distance : intérêt de la normalisation allométrique

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Received 4 February 2013; accepted 23 February 2013
Available online 6 June 2013

SUMMARY

Objectives. – The purpose of the present review was to investigate the influence of allometric scaling on the capacity to predict running performance using running efficiency (REff) values.

News. – REff, defined as oxygen consumption per unit distance, is believed to be a factor that is useful in the prediction of middle- and long-distance running performance. However, among factors that affect the relationship between REff and long-distance running performance, some authors have investigated the way in which body size impacts performance. Several studies support the use of allometric scaling and authors have tried to demonstrate that an indiscriminate use of the unit ml·kg⁻¹·min⁻¹ for oxygen consumption (VO₂) is inappropriate for comparing VO₂ values between subjects of different body characteristics.

Prospects and projects. – To date, the role of allometric scaling in the relationship between REff and the performance of long-distance runners has not been clearly demonstrated, even if there is some evidence that the use of kg⁻¹ is not appropriate.

Conclusions. – Further studies are needed to investigate the ways in which allometric scaling can be used to predict running performance using REff values.

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KEYWORDS

Allometric model; Bodyweight; Energy cost; Running economy

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http://dx.doi.org/10.1016/j.scispo.2013.02.007
MOTS CLÉS
Modèle allométrique ;
Masse corporelle ;
Coût énergétique ;
Économie de course

1. Introduction

Running efficiency (REff) is classically assessed in terms of the energy required to run at a given submaximal velocity (running economy - RE) [1], or the metabolic energy expended per unit of distance (energy cost of running - Cr) [2]. In existing literature, it is classically suggested that REff is an important factor that can be used to predict middle- and long-distance running performance [3–9]. According to initial reports by Daniels [8], REff can vary by more than 30% among runners who have a similar maximal oxygen uptake (VO₂max). However, despite the fact that the importance of REff on running performance has been recognized since the 1970s, this factor remains relatively ignored in existing scientific literature compared to other performance factors; for example, VO₂max and the ability to sustain a high percentage of VO₂max for an extended period of time [3].

Among the factors that affect the relationship between REff and long-distance running performance, some authors have investigated the way in which an athlete’s body size affects their performance [10–15]. Examining the anthropometric characteristics of top athletes could provide an indication of the directions of this effect [13]. Long-distance runners tend to be lighter than both rowers [16] and cross-country skiers [17]. Moreover, long-distance runners usually weigh less than the average person of comparable age and sex, indicating that individuals who are light have an advantage in this particular event [13].

To take into account the effect of body mass when comparing individuals with different morphology, some researchers have suggested the use of allometric scaling for efficiency assessment [10–15,18–22]. Allometric scaling is a methodological approach that was first proposed by Rubner [23] but has more recently been applied in health sciences [24] or human movement sciences [11,12,15,21,22,25–32].

In studies that support the use of allometric scaling, authors try to demonstrate that an indiscriminate use of the unit ml·kg⁻¹·min⁻¹ is inappropriate for the purposes of comparing oxygen consumption between subjects of different body characteristics. In one of the first studies, Von Dobelin [33] found that VO₂max was related to fat-free body mass raised to the power of 0.71 in a mixed population (both sexes). More recently, Bergh, Sjodin, Forsberg and Svedenhag [13] indicated that oxygen consumption during running does not increase proportionally to body mass and, as such, they proposed that in maximal or submaximal intensity, oxygen consumption needs to be relativized to kg⁻³⁄₄ and kg⁻⁵⁄₃, as opposed to kg⁻¹. Furthermore, Sjodin and Svedenhag [34] suggested that changes in REff and VO₂max in adolescent boys during growth may be largely due to an overestimation of oxygen consumption, justifying the use of allometric models. However, the role of this normalization in the relationship between REff and long-distance running performance has not been clearly demonstrated, even if some arguments indicate that it could improve performance predictions [3].

The purpose of the present review article was to investigate the influence of allometric scaling on the capacity to predict running performance using REff values.

2. Metabolic rate and allometric scaling

The relationship between body mass and metabolic rate has attracted the interest of biologists and healthcare professionals throughout the world [12,14,35,36]. Since the early studies of Rubner [23] and Kleiber [37], some studies have been developed with the goal of understanding the relationship between metabolic rate and allometric exponent [12,36].

Rubner demonstrated the existence of the relationship between metabolic rate and body size of dogs. According to their study, small dogs have higher metabolic rates per kilogram body mass than larger dogs. He found that there was a relationship between metabolic rate and ½ of body mass (r = 0.71); [38]. In 1932, Kleiber studied the relationship between metabolic rate and body mass and,
using rats and birds of different sizes, he found a higher metabolic rate with an allometric exponent to $\frac{3}{4}$ of body mass ($r = 0.98$), which was different than that proposed by Rubner. To confirm his findings, Kleiber [39] published a further study that demonstrated the existence of a relationship between metabolic rate and $\frac{3}{4}$ of mammalian body mass of different sizes (Fig. 1).

For both researchers, metabolic rate can be determined by a regression equation (equation (1)) that indicates the behavior of variable $Y$ on body mass $X$, where $a$ corresponds to the vertical interception, called the allometric coefficient (constant characteristic for the organism), and $b$ is the allometric or scaling exponent [11,19,36].

$$Y = aX^b$$

(1)

The exponential function can be transformed into a linear function (equation (2)):

$$\ln Y = \ln a + b \ln X$$

(2)

When the allometric exponent is 1 (equation (1)), the relationship is isometric and when it is different, the relationship is allometric.

In 1997, a new model was proposed for determining metabolic rate that was based on energy minimization and the fractal geometry of the distribution of nutrients. According to West, Brown and Enquist [18] Kleiber’s law ($b = \frac{3}{4}$) represents a practical means of characterizing the metabolic rate of all organisms. However, there is still a debate around the exponent and some researchers believe that the metabolic rate is governed by an allometric exponent to two-thirds of body mass, as per Rubner’s theory, which was based on the amount of total body surface [40,41]. Others still believe that there is a specific value of exponent allometric that depends on the group investigated [12,13,28,42].

Many variables and biological processes in birds and mammals appear to have exponents near approximately one-third, such as the cycle of breathing, the time of puberty, etc. Moreover, recent empirical investigations have confirmed that the allometric exponent of maximal metabolic rate is greater than the basal metabolic rate [43], a result not previously predicted by any theoretical model [44]. Furthermore, some conceptual and mathematical errors have been identified in the main models proposed to explain the origin of the exponent three-quarter metabolic rate [40,43], weakening the theoretical support of Kleiber’s law and strengthening the argument pertaining to the existence of specific allometric exponents.

Banavar et al. [45] and West et al. [18] proposed that allometric scaling, or scale metabolic, may be understood in terms of bases that limit supply and/or physiological processes that contribute to the regulation of metabolic rate, as proposed later by Darveau et al. [19], Hochachka et al. [46] and others (Fig. 2). This demonstrates the existence of specific allometric exponents and is contrary to the theories proposed by Rubner (in 1983) ($b = \frac{1}{3}$) and Kleiber (in 1932) ($b = \frac{3}{4}$). However, Dodds et al. [40], who analyzed the metabolic rate of 391 mammal species and 398 bird species, found that the scientific basis for completely rejecting the

![Figure 1](Author's personal copy) Proportionality between metabolic rate and $\frac{3}{4}$ body mass [39].

![Figure 2](Author's personal copy) a: for maximum metabolic rate (MMR), the functions listed in order are control coefficient ($c_i$), alveolar ventilation ($V_A$), pulmonary diffusion ($D_{lung}$), cardiac output ($Q$), capillary-mitochondria tissue diffusion ($D_{tissue}$), cytosolic and mitochondrial metabolism ($M_{mito}$) plus actomyosin ATPase (ATPase) and the Ca$^{2+}$ pump. The same abbreviations are used in b, in addition to the Na$^+$ pump and protein, urea and glucose synthesis. The two sets of $C_i$ values yield estimates of maximum ($b_{max}$) and minimum ($b_{min}$) values for scaling of MMR and basal metabolic rate (BMR).

Darveau et al., 2002.
allometric exponent of two-thirds proposed by Rubner, based on body surface, was insufficient.

Recently, new studies have emerged, mainly as a result of the work completed by exercise physiologists, which argue that the allometric exponent is morphologically specific according to the group investigated, i.e., each group has a specific allometric exponent [12,27–32,47]. Although studies have demonstrated the efficacy of allometric scaling for predicting various physiological parameters, further studies need to be developed by professional science of human movement experts that investigate the relationship between metabolic rate, body mass, body surface and physical performance.

3. Running efficiency and long-distance performance prediction: influence of allometric scaling

Locomotor performance is ultimately determined by the quantities of useful force and mechanical power that an animal can generate and sustain. It is the application of this force and mechanical power that accelerates the animal, supports its centre of mass, and overcomes friction, inertia, and wind resistance while running [48,49]. The quantities of useful force and mechanical power can be generated during locomotion and these are functions of physiological and biomechanical variables such as skeletal muscle metabolic capacity and energy cost [35].

Therefore, long-distance running performances depend on several physical, physiological, biomechanical, technological or psychological factors [2–4,9,50]. In particular:

- a high value of \( \dot{V}_{O_{2\text{max}}} \);
- a high fraction of \( \dot{V}_{O_{2\text{max}}} \), which can be sustained throughout the competition;
- and a better \( \text{REff} \) [51].

Within this framework, even if high correlations have been identified between \( \dot{V}_{O_{2\text{max}}} \) and the running performance of groups of runners with different running abilities [52], in groups of athletes of similar athletic capacities, \( \dot{V}_{O_{2\text{max}}} \) becomes a less sensitive predictor of performance, demonstrating the need to use other factors, such as the \( \text{REff} \), to predict long-distance running performance [1,52]. For example, over a 5-year period Jones [53] observed an 8% increase in the 3000 m running speed of an Olympic runner, whereas over the same period \( \dot{V}_{O_{2\text{max}}} \) decreased by 10%. The fall of \( \dot{V}_{O_{2\text{max}}} \) was compensated by an improvement in \( \text{REff} \) and an increase of the lactate threshold from 80 to 88% \( \dot{V}_{O_{2\text{max}}} \), thus suggesting an increase of the fraction of \( \dot{V}_{O_{2\text{max}}} \) sustainable throughout the effort, and demonstrating the important effect that \( \text{REff} \) can have on long-distance running performance.

The relationship between \( \text{REff} \) and performance during long-distance running has been studied since the early 1970s. Results suggest that it is an important factor in explaining performance in these events and it has also been proposed that a decrease of \( \text{REff} \) throughout an event could explain the worst performance observed in some runners [9,54], although \( \text{REff} \) has been studied relatively less than other factors [3].

At a given running speed, the submaximal oxygen requirement (per mL kg\(^{-1}\)·min\(^{-1}\)) may vary considerably between subjects [55]. For example a large variation in \( \text{REff} \) (about 20%) at a given speed has been observed between marathon runners of different performance capacities [52]. In contrast, the differences may be small or nonexistent when groups of elite runners from different distances are compared [56]. The \( \text{REff} \) of elite distance runners that are morphologically similar and exhibit a relatively narrow range in \( \dot{V}_{O_{2\text{max}}} \), has been proven to be significantly correlated (\( r=0.79–0.83 \)) at different speeds with performance during a 10 km race [54]. Interest in \( \text{REff} \) as an issue of real importance has increased in parallel with the emergence of runners of East African origin, as athletes from this area of the world have become dominant in competitive events over the last 20 years [57,58]. According to Foster and Lucia [3], individuals of East African origin may be systematically more economical because they have a smaller body size and a thinner lower leg. An ethnic difference appears to exist with regard to \( \text{REff} \) (Table 1). The studies by Coetzee et al. [59] and Saltin et al. [58], who each investigated South and Eastern Africans respectively, who are morphologically different individuals, implied that these people exhibit lower \( \text{Cr} \) (10%), (i.e., a better \( \text{REff} \)), than Caucasians. Furthermore, thus, when the 10 km race times of well-trained black and white South African runners with similar body size were compared, the former demonstrated the lowest \( \text{Cr} \) when running, regardless of whether this was expressed per kg or using two-third or three-quarter of body mass [60]. However, there is a lack of consensus on this argument. Bosch et al. [61] found the same \( \text{REff} \) in black and white South African marathon runners with varying performance levels. Using “scaling” there was a difference, with the black South African marathon runners having the lowest value (519 vs. 555 mL kg\(^{-0.75}\)·km\(^{-1}\))-Table 1).

Classical studies could test the effect of the mass distribution and help to understand the results of previous research. In determining race speed, the internal positive work performed by the lower limbs is about 40% of the total mechanical work performed by muscle-tendon units [62,63]. This rationale was already proposed from an evaluative point-of-view, where it was found that subjects with relatively longer lower limbs tend to have lower \( \text{Cr} \) than those with relatively shorter lower limbs [64]. Future stud-

<table>
<thead>
<tr>
<th>Population</th>
<th>Maximal oxygen uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{mL·kg}^{-1}·\text{min}^{-1} )</td>
</tr>
<tr>
<td>Reference value (ACSM) (80 kg)</td>
<td>58</td>
</tr>
<tr>
<td>Elite Europeans/ North Americans (65 kg)</td>
<td>55</td>
</tr>
<tr>
<td>Elite East Africans (60 kg)</td>
<td>50</td>
</tr>
</tbody>
</table>

ies should quantify the effects the mass of the lower limbs and their distribution on total mechanical work has on REff and performance in elite runners. Ferretti et al. [65] suggested that the ethnic difference in REff might be attributed to differences in the recoil of elastic energy stored in the stretched tendons, which decreases the metabolic energy spent at a given speed.

The role of body characteristics in long-distance performance entails that it may be useful to use allometric scaling to investigate the relationship between REff and long-distance performance. With the aim of trying to better understand the relationship between REff and performance, several studies have used allometric models, mainly to compare the morphologically of different individuals [66,67] and/or subjects with different types of locomotion [12,68]. According to these studies, relative values should be used to generate comparisons between individuals of different body masses and surface with an allometric exponent that could be specific of the group investigated [10,12,69].

In one of the first studies that used an allometric exponent to express efficiency of running, Bergh et al. [13] found that oxygen consumption during running is better related using specific allometric exponents, for example, kg$^{-0.24}$ and kg$^{-0.52}$, than to kg$^{-1}$. Furthermore, Sjodin and Svedenhag [34] suggested that changes in REff and VO$_{2\text{max}}$(per ml kg$^{-1}$min$^{-1}$) in adolescent boys during growth may be largely due to an overestimation of the oxygen consumption dependence of body mass during running. With an increasing age and body mass during growth, both VO$_{2\text{submax}}$ and VO$_{2\text{max}}$ will decrease differently according to the physical condition, suggesting the use of specific allometric exponents.

With the aim of identifying the optimal aerobic determinants of elite, distance-running performance using proportional allometric models, Ingham et al. [14] demonstrated that a proportional curvilinear ratio of VO$_{2\text{max}}$ divided by REff explains 95.9% of the variance in middle-distance running. In 1976, Winter and Hamley [70] had already demonstrated a significant linear relationship between VO$_{2\text{submax}}$, relativized by fat-free mass and lean leg volume, and treadmill speed in 32 trained male middle- and long-distance runners, thus demonstrating the importance of the relativization of REff.

In a more recent study that involved both runners and rowers, Tartaruga et al. [12] found significant changes in rank order in rowers with the use of an allometric exponent ($b=0.66$), demonstrating the importance of allometry in predicting performance in these kind of events (Table 2). However, in this previous study, the role of allometric scaling was not observed in runners with an exponent close to 1 ($b=0.99$) (Table 3).

The results acquired from running could be compared with a previous study by Nevill et al. [20], in which a group of recreationally active adults, both men and women, were investigated. In this study, the authors found that using VO$_{2\text{max}}$ (per L min$^{-1}$) and body mass ($m$) as predictor variables, the best predictor model of 5-km running performance was:

$$\text{Run speed (m s}^{-1}) = 84.3 (\text{VO}_{2\text{max}})^{1.03} (m)^{-1.03}$$

With both exponents close to unity but with opposite signs, their model suggested that the REff of 5-km run speeds was almost exactly proportional to the traditional ratio standard using oxygen consumption (per L min$^{-1}$) divided by body mass (in kg) or oxygen consumption (per ml kg$^{-1}$ min$^{-1}$) [47]. A similar result was obtained when investigating the REff of 12-year-old boys [22]. The authors confirmed that the best predictor of boys’ 1 mile run speed was the traditional ratio standard, VO$_{2\text{max}}$ (per ml kg$^{-1}$ min$^{-1}$).

**Table 2** Reference values for VO$_{2\text{submax}}$ in 15 rowers.

<table>
<thead>
<tr>
<th>Submaximal oxygen uptake</th>
<th>mL kg$^{-1}$ min$^{-1}$</th>
<th>mL kg$^{-0.68}$ min$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rower 01</td>
<td>36.5</td>
<td>146.5</td>
</tr>
<tr>
<td>Rower 02</td>
<td>37.2</td>
<td>147.4</td>
</tr>
<tr>
<td>Rower 03</td>
<td>37.6</td>
<td>149.8</td>
</tr>
<tr>
<td>Rower 04</td>
<td>37.8</td>
<td>150.7</td>
</tr>
<tr>
<td>Rower 05</td>
<td>38.5</td>
<td>152.8</td>
</tr>
<tr>
<td>Rower 06</td>
<td>39.1</td>
<td>153.3</td>
</tr>
<tr>
<td>Rower 07</td>
<td>40.0</td>
<td>154.4</td>
</tr>
<tr>
<td>Rower 08</td>
<td>40.4</td>
<td>158.3</td>
</tr>
<tr>
<td>Rower 09</td>
<td>41.0</td>
<td>160.9</td>
</tr>
<tr>
<td>Rower 10</td>
<td>41.2</td>
<td>162.6</td>
</tr>
<tr>
<td>Rower 11</td>
<td>42.1</td>
<td>163.6</td>
</tr>
<tr>
<td>Rower 12</td>
<td>42.3</td>
<td>163.7</td>
</tr>
<tr>
<td>Rower 13</td>
<td>42.6</td>
<td>164.5</td>
</tr>
<tr>
<td>Rower 14</td>
<td>42.8</td>
<td>170.3</td>
</tr>
<tr>
<td>Rower 15</td>
<td>42.9</td>
<td>172.8</td>
</tr>
</tbody>
</table>

Tartaruga et al., 2010.

**Table 3** Reference values for VO$_{2\text{submax}}$ in 11 runners.

<table>
<thead>
<tr>
<th>Submaximal oxygen uptake</th>
<th>mL kg$^{-1}$ min$^{-1}$</th>
<th>mL kg$^{-0.99}$ min$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runner 01</td>
<td>41.0</td>
<td>42.7</td>
</tr>
<tr>
<td>Runner 02</td>
<td>41.5</td>
<td>43.2</td>
</tr>
<tr>
<td>Runner 03</td>
<td>43.0</td>
<td>44.8</td>
</tr>
<tr>
<td>Runner 04</td>
<td>44.2</td>
<td>46.0</td>
</tr>
<tr>
<td>Runner 05</td>
<td>44.6</td>
<td>46.3</td>
</tr>
<tr>
<td>Runner 06</td>
<td>45.5</td>
<td>47.4</td>
</tr>
<tr>
<td>Runner 07</td>
<td>46.1</td>
<td>48.1</td>
</tr>
<tr>
<td>Runner 08</td>
<td>46.5</td>
<td>48.3</td>
</tr>
<tr>
<td>Runner 09</td>
<td>46.8</td>
<td>48.8</td>
</tr>
<tr>
<td>Runner 10</td>
<td>47.3</td>
<td>49.4</td>
</tr>
<tr>
<td>Runner 11</td>
<td>51.2</td>
<td>53.4</td>
</tr>
</tbody>
</table>

Tartaruga et al., 2010.

Submaximal oxygen uptake (VO$_{2\text{submax}}$).
4. Conclusion

Previous research indicates that $Reff$ is clearly an important predictor of long-distance running performance. Existing research indicates that oxygen consumption does not increase proportionally to body mass in running [3,10,13,22] or in other sports, i.e., rowing [12,21], and bicycling [26]. Therefore, dividing oxygen uptake by body mass may induce erroneous interpretations when comparing individuals or groups who differ in body mass. In weight-supported events, studies have demonstrated that allometric scaling can improve the relationship between $Reff$ and performance. However, this result is not clearly demonstrated for running, despite the important role that body characteristics can play in explaining performance. Thus, there is a need to conduct further studies that investigate the ways in which allometric scaling can be used to predict running performance using $Reff$ values.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Acknowledgments

This study was supported by CAPES - Brazil.

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Allometric scaling and running performance


