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RELAÇÃO DA ECONOMIA DE CORRIDA E DA EFICIÊNCIA MECÂNICA COM
O DESEMPENHO DE CORREDORES DE RENDIMENTO USANDO MODELOS
ALOMÉTRICOS

RELATION DE L'ÉCONOMIE DE COURSE ET L'EFFICIENCE MÉCANIQUE SUR
LA PERFORMANCE DES ATHLÈTES DE LONGUES DISTANCES UTILISANT
DES MODÈLES ALLOMÉTRIQUES

THESIS

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“Todas as vitórias ocultam uma abdicação” (Simone de Beauvoir)

“Toute réussite déguise une abdication”

“A persistência é o menor caminho do êxito” (Charles Chaplin)

“La persistance est le plus court chemin vers le succès”

“O conhecimento nos faz responsáveis” (Che Guevara)

“La connaissance nous rend responsables”

RESUMO (PORTUGUÊS)

O objetivo do presente estudo foi analisar as relações da economia de corrida (ECO) e da eficiência mecânica (Ef) com o desempenho de corredores de rendimento, utilizando modelos alométricos. No estudo original I, 13 corredores recreacionistas (homens; idade: $33,3 \pm 8,4$ anos; massa corporal: $76,4 \pm 8,6$ kg; consumo máximo de oxigênio - $VO_{2m\acute{a}x}$: $52,8 \pm 4,6$ ml·kg⁻¹·min⁻¹) e 13 corredores de alto-rendimento (homens; idade: $25,5 \pm 4,2$ anos; massa corporal: $62,8 \pm 2,7$ kg; $VO_{2m\acute{a}x}$: $70,4 \pm 1,9$ ml·kg⁻¹·min⁻¹), todos praticantes de provas de meio-fundo, realizaram um teste máximo de esforço progressivo, até a exaustão, com o intuito de determinar o valor de $VO_{2m\acute{a}x}$, e um teste de ECO com duração de 6-min à 70% do $VO_{2m\acute{a}x}$ para a mensuração do consumo submáximo de oxigênio ($VO_{2subm\acute{a}x}$), com e sem a aplicação de um expoente alométrico (b) específico correspondente a 0,75, determinado através da relação alométrica $y = ax^b$, onde y corresponde à taxa metabólica máxima, a ao coeficiente alométrico, e x à massa corporal. Todos os corredores, também, participaram de uma prova de meia-distância em uma pista de atletismo. Neste estudo, investigou-se o efeito da escala alométrica na relação entre ECO e desempenho em prova de meia-distância, de acordo com o condicionamento cardiorrespiratório. No estudo original II, 14 corredores recreacionistas (homens; idade: $29,0 \pm 7,0$ anos; massa corporal: $70,0 \pm 10,2$ kg; $VO_{2m\acute{a}x}$: $52,0 \pm 4,9$ ml·kg⁻¹·min⁻¹), praticantes de corridas de longa-distância, também realizaram um teste máximo de esforço progressivo, até a exaustão, para a determinação do $VO_{2m\acute{a}x}$, e um teste de ECO com duração de 6-min à $3,1$ m·s⁻¹ para a determinação do $VO_{2subm\acute{a}x}$. Durante o teste submáximo, foi realizada uma videometria no plano sagital direito de cada sujeito com o objetivo de mensurar os trabalhos mecânicos interno (W_{int}), externo (W_{ext}) e total (W_{tot}) e, posteriormente, relacioná-los com o desempenho em prova de rua de 10.000 m, com e sem o uso de expoentes alométricos específicos. Para este estudo foram adotados os expoentes alométricos correspondentes a 0,75, sugerido pela literatura, e 0,45, determinado matematicamente. No estudo original III, 13 corredores recreacionistas (homens; idade: $33,3 \pm 8,4$ anos; massa corporal: $76,4 \pm 8,6$ kg; $VO_{2m\acute{a}x}$: $52,8 \pm 4,6$ ml·kg⁻¹·min⁻¹) realizaram um teste máximo de esforço progressivo, até a exaustão, um teste de ECO dividido em três testes submáximos (50%, 70% e 90% do $VO_{2m\acute{a}x}$), com duração 6-min cada, e um teste supra-máximo voluntário, até a exaustão, correspondente a 110% da velocidade no $VO_{2m\acute{a}x}$. Após os testes laboratoriais, todos os corredores participaram de uma prova de 10.000-m em uma pista de atletismo. Para cada sujeito, a técnica de corrida foi registrada cinematicamente utilizando-se 4 câmeras digitais de alta frequência. Com o objetivo de investigar a relação da ECO e da Ef com o desempenho de corredores de rendimento, usando modelos alométricos, foram determinados os expoentes alométricos correspondentes às taxas metabólicas máxima e submáxima (0,84 e 0,76, respectivamente). A contribuição das energias aeróbica (AE) e anaeróbica (AnE) no custo energético da corrida (C_r) também foi investigada. Foi aplicada a estatística descritiva através de médias e desvios-padrão e o teste Shapiro-Wilk para verificação da normalidade dos dados. Foram empregados os testes T de *Students* para amostras dependentes e independentes, as análises de correlação de Pearson e de Regressão Linear Múltipla e, a transformação de Fisher *r-to-z*. A partir dos resultados apresentados nos três estudo originais, conclui-se que a escala alométrica pode melhorar a relação entre ECO e desempenho em meia e longa-distância,

principalmente de corredores recreacionistas, devido a influência dos aspectos morfofuncionais no desempenho físico. Da mesma forma, para esta mesma população, os trabalhos mecânicos, especialmente o W_{ext} , podem ser considerados preditores do desempenho, e um expoente alométrico específico pode melhorar essas previsões. Em relação a E_f , os resultados demonstraram que, assim como ocorre com a ECO e com os trabalhos mecânicos, esta também é uma importante variável preditora do desempenho em provas de longa-distância. Entretanto, quando aplicada a alometria, não houve melhora na previsão do desempenho advindo da E_f . Os resultados também demonstraram que para o cálculo da E_f deve-se considerar a contribuição da AnE pois, do contrário, os resultados podem ser superestimados, como já verificados em outros estudos. Em suma, quando o objetivo for prever o desempenho de corredores recreacionistas, meio-fundistas ou fundistas, através das potências metabólica ou mecânica, sugere-se adotar um expoente alométrico específico do grupo investigado. No entanto, quando essa previsão for realizada considerando-se a E_f , especificamente em corredores de alto-rendimento, a aplicação alométrica não é necessária.

RESUME (FRANÇAIS)

Le but de cette étude était d'analyser la relation entre l'économie de course à pied (ECO) et l'efficacité mécanique (Eff) dans la performance des coureurs spécialistes en moyenne et longue distance, utilisant des modèles allométriques. Dans l'étude originale I, 13 coureurs amateurs (hommes, âge : 33.3 ± 8.4 ans, poids corporel : 76.4 ± 8.6 kg, consommation maximale d'oxygène - VO_{2max} : 52.8 ± 4.6 ml·kg⁻¹·min⁻¹) et 13 coureurs d'haut niveau (hommes, âge : 25.5 ± 4.2 ans, poids corporel : 62.8 ± 2.7 kg, VO_{2max} : 70.4 ± 1.9 ml·kg⁻¹·min⁻¹), tous spécialistes en preuves de moyenne distance, ont effectué un test progressif maximal afin de déterminer les valeurs de VO_{2max} , et un test de ECO de 6-min à 70% du VO_{2max} pour mesurer la consommation d'oxygène sous-maximale ($VO_{2submax}$), avec et sans l'application d'un exposant allométrique (b) spécifique correspondant à déterminée par la relation allométrique $y = ax^b$, où y correspond à la taux métabolique maximal, a au coefficient allométrique et x à la masse corporelle. Tous les coureurs également ont participé de une course à pied de moyenne distance en une piste de athlétisme. Dans cette étude, nous avons étudié l'effet de l'échelle allométrique dans la relation entre ECO et performance, selon le conditionnement cardiorespiratoire. Dans l'étude original II, 14 coureurs amateurs (hommes, âge : 29.0 ± 7.0 ans, poids corporel : 70.0 ± 10.2 kg, VO_{2max} : 52.0 ± 4.9 ml·kg⁻¹·min⁻¹), spécialistes en longue distance, également ont effectué un test progressif maximal afin de déterminer les valeurs de VO_{2max} , et un test de ECO de 6-min à 3.1 m·s⁻¹ pour évaluer le $VO_{2submax}$. Pendant le test sous-maximal a été effectuée un registre cinématique afin de mesurer le travail mécanique interne (W_{int}), externe (W_{ext}) et total (W_{tot}) et, après, les relier à la performance en 10.000 de course à pied, avec et sans l'utilisation des exposants allométriques spécifiques. Pour cette étude, nous avons adopté les exposants allométriques correspondant à 0.75, suggérées par la littérature, et 0.45, spécifique du group de sujets évalués. Dans l'étude original III, 13 coureurs amateurs (hommes, âge : 33.3 ± 8.4 ans, poids corporel : 76.4 ± 8.6 kg, VO_{2max} : 52.8 ± 4.6 ml·kg⁻¹·min⁻¹) ont effectué un test progressif maximal, un test d'ECO composé de trois intensités sous-maximales correspondants à 50%, 70% et 90% du VO_{2max} avec une durée de 6-min chacun et,

un test supramaximal correspondant à 110% de la vitesse du VO_{2max} . Après des tests en laboratoire, tous les coureurs ont participé de une course à pied de 10.000-m en une piste de athlétisme où la technique a été enregistrée cinématiquement avec des quatre caméscopes de haute fréquence. Afin d'étudier des relations de l'ECO et l'Eff avec la performance des coureurs expertises en longue distance, ont été déterminées des exposants allométriques correspondant au taux métabolique en situations maximal et sous-maximal (0.84 et 0.76, respectivement). La contribution de l'énergie aérobie (AE) et anaérobie (AnE) dans le coût énergétique en course à pied (C_r) a été évaluée. Nous avons utilisé des statistiques descriptives (moyenne et écarts-types) et le test de Shapiro-Wilk pour vérifier la normalité des données. Les tests T de *Student* dépendant et indépendant, des analyses de corrélation de Pearson et de Régression Linéaire Multiple et, la transformation de Fisher *r-to-z* ont été réalisés. Selon les résultats, l'échelle allométrique peut améliorer la relation entre ECO et performance dans la course à pied de moyenne et longue distance, principalement en coureurs amateurs, pour raison morpho-fonctionnelles. Également, pour cette même population, des travaux mécaniques, principalement le W_{ext} , peut être considérées comme prédicteurs de la performance de la course à pied de sujets spécialistes en longue distance, et un exposant allométrique peut améliorer cette prédiction. En ce qui concerne à l'Eff, les résultats ont montré que, comme également occur avec l'ECO et les travaux mécaniques, cette variable est, aussi, une important variable de prédiction de la performance en preuves de longue distances. Toutefois, quand appliqué des exposant allométriques, il n'y avait aucune amélioration dans cette prédiction, principalement en coureurs de haut niveau. Les résultats ont montré, aussi, que pour le calcul de l'Eff, la contribution AnE est important, parce que, contrairement, les résultats peuvent être surestimés comme déjà signalé en autres études. En général, lorsque l'objectif est prédit la performance des coureurs amateurs de moyenne ou de longue distance, à travers des puissances métaboliques ou mécaniques, est suggéré d'adopter un exposant allométrique spécifique du groupe étudié. Toutefois, lorsque cette prédiction est réalisée avec la utilisation de l'Eff en un group de coureurs de haut niveau, l'échelle allométrique n'est pas indiquée.

DECLARATION OF ORIGINALITY AND AUTHORSHIP

I, Marcus Peikriszwili Tartaruga, hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources.

Signed the 22 - 9 - 2013 in Porto Alegre, Brazil

A handwritten signature in black ink, reading "Marcus P. Tartaruga". The signature is written in a cursive style with a long horizontal stroke extending to the right.

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LISTA DE ABREVIACOES

Portugus	Nome		
g	Acelerao da gravidade	EPE	Energia potencial elstica
ATP	Adenosina trifosfato	EPG	Energia potencial gravitacional
Ca ⁺² _{bomba}	Bomba de clcio	E _{tot}	Energia total
NA ⁺ _{bomba}	Bomba de sdio	b	Expoente alomtrico
CHO	Carboidrato	FC	Frequncia cardica
CM _c	Centro de massa corporal	ATPase	Hidrlise de adenosina trifosfato
CM _s	Centro de massa segmentar	LA	Limiar anaerbico
a	Coefficiente alomtrico	Ln	Logartmico natural
L	Comprimento de membro inferior	x, MC	Massa corporal
VO _{2mx}	Consumo mximo de oxignio	MAOD	Mximo dficit acumulado de oxignio
VO _{2submx}	Consumo submximo de oxignio	M _{mito}	Metabolismo citoslico e mitocondrial
C _{transp}	Custo de transporte	NF	Nmero de Froude
C _r	Custo energtico em corrida	Q _{mc}	Quantidade de massa corporal
C _{met}	Custo metablico	y, TM	Taxa metablica
Q	Dbito cardico	TMB	Taxa metablica basal
D _{pulmonar}	Difuso pulmonar	TMM	Taxa metablica mxima
D _{tecdual}	Difuso tecdual capilar-mitocndria	W _{ext}	Trabalho mecnico externo
ECO	Economia de corrida	W _{int}	Trabalho mecnico interno
Ef	Efcincia mecnica	W _{tot}	Trabalho mecnico total
AE	Energia aerbica	v	Velocidade
AnE	Energia anaerbica	V _A	Ventilao alveolar
EC	Energia cintica		

Franais	Nom		
a	Coefficient allomtrique	AnE	nergie anarobique
VO _{2submax}	Consommation d'oxygne sous-maximale	b	Exposant allomtrique
VO _{2max}	Consommation maximale d'oxygne	x	Masse corporelle
C _r	Cot nergtique en course  pied	y	Taux mtabolique maximal
ECO	conomie de course	W _{ext}	Travail mcanique externe
Eff	Efficience mcanique	W _{int}	Travail mcanique interne
AE	nergie arobique	W _{tot}	Travail mcanique total

English	Name		
ATPase	Actomyosin ATPase	V _{ap}	Antero-posterior velocities of the CM
ATP	Adenosine triphosphate	BMR	Basal metabolic rate
C _{rAE}	Aerobic cost of running	E _{CM} , CM	Body centre of mass
a	Allometric coefficient	x, m, BM	Body mass
V _A	Alveolar ventilation	D _{tissue}	Capillary-mitochondria tissue diffusion
C _{rAnE}	Anaerobic cost of running	Q	Cardiac output
AT	Anaerobic threshold	c _i	Control coefficient
ω	Angular velocity	M _{mito}	Cytosolic and mitochondria metabolism
V _{ap,r}	Antero-posterior velocities of each segment	Cr	Energy cost of running

W_{ext}	External mechanic work	VO_2	Oxygen consumption
PE	Gravitational potential energy	D_{lung}	Pulmonary diffusion
h	Height of the body centre of mass	RE	Running economy
W_{int}	Internal mechanic work	REff	Running efficiency
KE	Kinetic energy	n	Sample
m	Mass of segment	b	Scaling exponent or allometric exponent
vW_{max}	Maximal aerobic velocity	K	Segment radius of gyration
$\text{VO}_{2\text{max}}$	Maximal oxygen uptake	$\text{VO}_{2\text{submax}}$	Submaximal oxygen uptake
$\text{VO}_{2\text{maxabs}}$	Maximal oxygen uptakes absolute	M	Total body mass
MMR	Maximum metabolic rate	TE	Total energy
ME	Mechanical efficiency	W_{tot}	Total mechanic work
ME_r	Mechanical efficiency of running locomotion	VE	Ventilation
Y, MR	Metabolic rate / absolute $\text{VO}_{2\text{max}}$	$V_{v,r}$	Vertical velocities of each segment
Log, ln	Natural logarithm	V_v	Vertical velocities of the CM

LIST OF RELEVANT PUBLICATIONS EXTRAS

ARTICLE I **Tartaruga MP**, Brisswalter J, Peyre-Tartaruga LA, Avila AO, Alberton CL, Coertjens M, Cadore EL, Tiggemann CL, Silva EM, Krueel LF (2012). The relationship between running economy and biomechanical variables in distance runners. *Res Q Exerc Sport*. 83:367-75. (Annex A)

ARTICLE II **Tartaruga MP**, Medeiros MHd, Alberton CL, Cadore EL, Peyré-Tartaruga LA, Baptista RR, Krueel LFM (2010). Application of the allometric scale for the submaximal oxygen uptake in runners and rowers. *Biol Sport*. 27:297-300. (Annex B)

ARTICLE III **Tartaruga MP**, Peyré-Tartaruga LA, Coertjens M, Medeiros MHd, Krueel LFM (2009). The influence of the allometric scale on the relationship between running economy and biomechanical variables in distance runners. *Biol Sport*. 26:263-273. (Annex C)

ARTICLE IV **Tartaruga MP**, Bailke DD, Coertjens M, Baptista RR, Tartaruga LAP, Krueel LFM (2008). Relação entre consumo máximo e submáximo de oxigênio em corredores e remadores de rendimento. *Rev. Ed Física*. 141:22-33. (Annex D)

LIST OF THESIS RELEVANT CONFERENCE PRESENTATIONS (2009 to 2013)

ORAL **Tartaruga MP**, Dos Santos MG, Tiggemann CL, Alberton CL ; Cadore EL, Da Silva EM, Peyré-Tartaruga LA, Coertjens M, Avila AOV, Krueel LFM (2009). Relação entre economia de corrida e variáveis biomecânicas em corredores fundistas. XIII Congresso Brasileiro de Biomecânica, São Paulo, Brasil.

POSTER **Tartaruga MP**, Mota CB, Peyré-Tartaruga LA, Brisswalter J (2013). Scaling running efficiency in recreational and high-level endurance runners: effect on performance prediction. 18th Annual Congress of the ECSS, Barcelona, Spain.

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INTRODUÇÃO

1.1. INTRODUÇÃO

Um organismo de maior massa corporal (MC) apresenta uma taxa metabólica (TM) maior que um organismo de menor MC, pois existe uma relação proporcional crescente entre MC e metabolismo (GILLOOLY *et al.*, 2001). Entretanto, o maior organismo poderá apresentar valores metabólicos menores quando estes forem normalizados pela MC total (JENSEN *et al.*, 2001; LOFTIN *et al.*, 2001). No primeiro caso, a TM é expressa de forma absoluta, através de uma unidade que representa a quantidade total da variável avaliada. No segundo caso, é expressa de forma relativa, através de uma unidade que representa a quantidade da variável avaliada para cada quilograma de MC.

Durante o exercício intenso considera-se o consumo máximo de oxigênio ($VO_{2m\acute{a}x}$) como uma das medidas para avaliação do condicionamento cardiorrespiratório. Ele pode ser expresso de forma absoluta ($L \cdot min^{-1}$) ou de forma relativa à MC total ($ml \cdot kg^{-1} \cdot min^{-1}$) (POWERS e HOWLEY, 2012). Os valores relativos são mais utilizados para comparações entre sujeitos que apresentam diferentes níveis de condicionamento físico (BASSETT e HOWLEY, 2000).

Especificamente na corrida de rendimento, os principais fatores fisiológicos que predizem o desempenho em provas de meia (800 a 5.000-m) e longa distância (10.000-m) são a economia de corrida (ECO) e o limiar anaeróbico (LA) (BASSETT e HOWLEY, 2000; FOSTER e LUCIA, 2007; NUMMELA *et al.*, 2007). A ECO é definida como o consumo de oxigênio em uma determinada velocidade submáxima de corrida ($VO_{2subm\acute{a}x}$) (WILLIAMS e CAVANAGH, 1987) ou o consumo de oxigênio em uma determinada distância, denominada de custo energético ou metabólico (C_{met}) (MARGARIA *et al.*, 1963). Esta pode ser responsável por até 30% do desempenho em provas de meia e longa distância (DANIELS *et al.*, 1978; FARRELL *et al.*, 1979; CONLEY e KRAHENBUHL, 1980; BASSETT e HOWLEY, 2000; SAUNDERS *et al.*, 2004). Já o LA, podendo ser determinado pelas respostas ventilatórias ou pelo comportamento da curva de lactacidemia (OWLES, 1930; WASSERMAN e McILROY, 1964; WASSERMAN *et al.*, 1973; COYLE, 1995; HOLLMANN, 2001) tem sido identificado, também, como um bom preditor do desempenho da corrida, respondendo por 72 à 92% da variação do desempenho para distâncias compreendidas entre 3,2 e 42,2 km (FARRELL *et al.*, 1979; SJODIN e JACOBS, 1981).

Entretanto, apesar da forte relação entre ECO e desempenho existente em corredores de rendimento de meia e longa distância, a relativização da ECO vem sofrendo algumas críticas. Acredita-se que a relativização do consumo de oxigênio pela MC total (kg^{-1}), tanto em intensidades máxima quanto em intensidades submáximas de esforço, não seja o melhor parâmetro de predição do desempenho e de comparação do condicionamento cardiorrespiratório entre sujeitos. Alguns autores apontam a necessidade da utilização de parâmetros que permitam que variáveis fisiológicas, como o consumo de oxigênio, sejam comparadas entre sujeitos com valores relativos de massas corporais diferentes da MC total (BRISWALTER *et al.*, 1996; WEST *et al.*, 1997; DARVEAU *et al.*, 2002).

A escala alométrica é um exemplo. Ela é representada por uma equação de regressão que indica o comportamento de uma variável fisiológica y em relação a variável massa x ($y = ax^b$). O coeficiente alométrico a é característico da espécie analisada - podendo ser o $VO_{2m\acute{a}x}$ absoluto - e o expoente alométrico b determina a parcela da MC a ser associada com a variável y . Esta

função exponencial pode ser transformada logaritmicamente em uma função linear através da equação $\ln y = \ln a + b \ln x$.

Na prática esportiva, poucos estudos têm verificado a necessidade de adotar diferentes expoentes alométricos para a determinação da quantidade de MC a ser utilizada na relativização do consumo de oxigênio. Estes valores seriam específicos para diferentes modalidades esportivas (JENSEN *et al.*, 2001) e para populações especiais (GOOSEY-TOLFREY *et al.*, 2003). Neste âmbito, afirma-se que a relativização parcial do consumo de oxigênio e da MC é adotada devido ao fato de existirem muitos tipos de locomoção e cada um requer uma quantidade de MC a ser sustentada e deslocada (SALTIN e ASTRAND, 1967). Entretanto, as maiores justificativas da aplicação da escala alométrica, principalmente na determinação da ECO, podem ser verificadas nas relações comprovadas do metabolismo corporal (DARVEAU *et al.*, 2002), da temperatura corporal (GILLOOLY *et al.*, 2001), do percentual de gordura corporal (KUSANO *et al.*, 1997) e do tamanho da superfície corporal (TARTARUGA *et al.*, 2009), esta determinante da capacidade de troca de calor com o meio externo (JENSEN *et al.*, 2001), com o consumo de oxigênio. Indiscutivelmente, cada sujeito apresenta uma particularidade no consumo de oxigênio resultante das diferenças fisiológicas de cada organismo. Dessa forma, relativizar o consumo de oxigênio individual pela MC total podem resultar em equívocos na comparação do condicionamento físico entre sujeitos. No caso da corrida, pode resultar em valores de ECO contraditórios.

Outros fatores que podem auxiliar na compreensão do desempenho em provas de meia e longa distância estão relacionados ao comportamento de variáveis mecânicas e energéticas da locomoção. Dois modelos mecânicos, o pêndulo-invertido e o sistema massa-mola, explicam como os mecanismos pendular e elástico minimizam o dispêndio energético advindo dos músculos durante a caminhada e a corrida humana, respectivamente (PEYRÉ-TARTARUGA, 2008). Na caminhada, a energia potencial gravitacional (EPG) é alta quando o centro de MC (CM_c) está sobre o ponto de contato do corpo com o solo, mas a partir deste momento, a EPG começa a diminuir e a energia cinética (EC) horizontal obtém um acréscimo gradativo. Quando o ponto de contato volta a estar na frente do CM_c a EC diminui e a EPG aumenta. Estes comportamentos entre EC horizontal e EPG acontecem em oposição de fase (CAVAGNA *et al.*, 1963) e, portanto, em um processo de reconversão (*Recovery*). Por outro lado, na corrida, os acréscimos de EC e EPG ocorrem concomitantemente, portanto o mecanismo de conservação de energia citado anteriormente não se aplica neste tipo de locomoção. É postulado que durante a primeira metade da fase de apoio da corrida, músculos e tendões se alongam armazenando energia potencial elástica (EPE), enquanto que os módulos de EC horizontal e EPG diminuem. Esta EPE, armazenada como uma mola comprimida por uma massa, é transformada em EC horizontal e em EPG de modo gradativo durante a segunda metade da fase de apoio (CAVAGNA *et al.*, 1964; KOMI, 2000).

Enquanto que a medida de trabalho mecânico externo (W_{ext}) possui uma correspondência com o trabalho mecânico realizado pelos músculos na caminhada, os valores obtidos para a corrida superestimam o trabalho muscular realizado devido à dificuldade de quantificar a EPE durante o movimento (SAIBENE e MINETTI, 2003). De fato, parte considerável do aumento e diminuição da energia mecânica total na corrida não é causada pelas contrações excêntricas e

concêntricas musculares, mas pelo alongamento e encurtamento das estruturas elásticas da unidade músculo-tendão. Portanto, na corrida, a adição do trabalho mecânico interno (W_{int}) e a transferência entre segmentos dos mesmos membros (inferiores e superiores) permitem uma estimativa mais próxima do trabalho mecânico total (W_{tot}), resultante, então, da soma do W_{int} e W_{ext} (WILLEMS *et al.*, 1995).

O conceito de eficiência mecânica (Ef) é integrado na locomoção mais tarde, sendo esta a capacidade de produzir W_{tot} com o menor $VO_{2submáx}$ possível (CAVAGNA *et al.*, 1977). O W_{int} , derivado do teorema da EC total de um sistema (teorema de Köning), já havia sido descrito por Fenn em 1930, e formalizado por Cavagna e Kaneko (1977). Entretanto, somente mais tarde sua relação com o W_{tot} foi preconizada (WILLEMS *et al.*, 1995). Mas a grande associação proposta pelos trabalhos citados anteriormente é de que o W_{tot} , calculado com base no comportamento do CM_c e do centro de massa de cada segmento corporal (CM_s) é resultante de fenômenos fisiológicos e mecânicos corporais. A Ef , advinda do quociente do W_{tot} pelo $VO_{2submáx}$ passa a ser, então, investigada em estudos relacionados à locomoção (KYROLAINEN *et al.*, 1995; SCHEPENS *et al.*, 2001; FROST *et al.*, 2002; MIAN *et al.*, 2006), porém, sem que haja uma maior preocupação na determinação da potência metabólica, ou seja, na escolha de um expoente alométrico específico da amostra para o cálculo desta variável.

Apesar das fortes relações verificadas na literatura da ECO e da Ef com o desempenho em provas de meia e longa distância, poucos estudos têm sido desenvolvidos com o objetivo de investigar a influência da escala alométrica no comportamento da ECO e da Ef , conseqüentemente, nas referidas relações. De acordo com diversos autores (MARGARIA *et al.*, 1963; CAVAGNA *et al.*, 1964; CAVAGNA *et al.*, 1976; CAVAGNA e KANEKO, 1977; MINETTI *et al.*, 1994; MINETTI *et al.*, 1995; WILLEMS *et al.*, 1995; MINETTI, 1998; MINETTI *et al.*, 2002; CAVAGNA *et al.*, 2008; CAVAGNA, 2010), a ECO e a Ef são variáveis resultantes do comportamento e da interação de parâmetros mecânicos e energéticos importantes para a locomoção. Acredita-se que com a aplicação de expoentes alométricos específicos as relações da ECO e da Ef com o desempenho de corredores de rendimento tornem-se mais precisas devido a utilização de valores de consumo de oxigênio mais representativos dos grupos investigados.

1.2. OBJETIVO

1.2.1. OBJETIVO GERAL DA TESE

Analisar as relações da ECO e da Ef com o desempenho de corredores de rendimento usando modelos alométricos.

REVISÃO BIBLIOGRÁFICA

2.1. A ESCALA METABÓLICA

A relação entre massa corporal (MC) e taxa metabólica (TM) tem despertado o interesse de pesquisadores de diversas áreas do conhecimento (JONES e LINDSTEDT, 1993; SUAREZ *et al.*, 2004; INGHAM *et al.*, 2008; TARTARUGA *et al.*, 2010). Desde os primeiros estudos de Rubner (1883) e Kleiber (1932), muitas pesquisas têm sido desenvolvidas com o objetivo de compreender melhor a relação entre TM e MC, com o uso de modelos alométricos específicos (SUAREZ *et al.*, 2004; TARTARUGA *et al.*, 2010).

Rubner (1883) demonstrou a existência da relação entre TM e tamanho corporal de cachorros. De acordo com seu estudo, pequenos cachorros apresentam maiores taxas metabólicas por quilograma de MC do que grandes cachorros. Ele verificou uma relação da TM com $\frac{2}{3}$ da MC ($r = 0,71$), o que representaria a relação entre TM e superfície corporal (TAYLOR *et al.*, 1970). Já Kleiber (1932) dando continuidade ao estudo da relação entre TM e MC, analisando ratos e aves de diferentes tamanhos, verificou que a TM apresentava maior proporcionalidade com $\frac{3}{4}$ da MC ($r = 0,98$) (KLEIBER, 1947; TAYLOR *et al.*, 1970), diferente do proposto por Rubner (1883), além de concluir que ela não estava relacionada apenas a superfície corporal como proposto por Rubner (1883). Para confirmar seus achados Kleiber (1947) publicou outro estudo comprovando, novamente, a existência da relação entre TM e $\frac{3}{4}$ da MC de mamíferos de diferentes tamanhos (Figura 1).

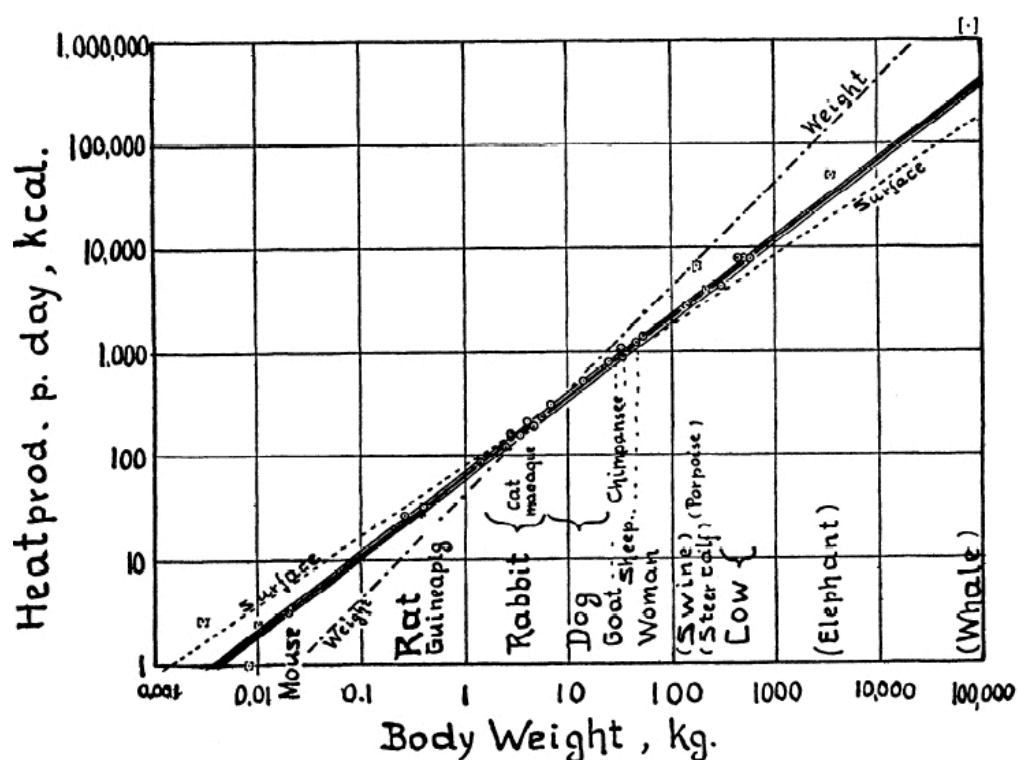


Figura 1 – Proporcionalidade entre TM e $MC^{3/4}$ Kleiber (1947).

Para ambos os pesquisadores, a TM pode ser determinada através de uma equação de regressão (Equação 1) que indica o comportamento desta variável (y) em relação a variável MC (x) (Equação 2).

$$y = ax^b \quad (1)$$

$$TM = aMC^b \quad (2)$$

onde a corresponde a intercepção vertical, também denominada de coeficiente alométrico, e b ao expoente alométrico (DARVEAU *et al.*, 2002; SUAREZ *et al.*, 2004; TARTARUGA *et al.*, 2009). Esta função exponencial alométrica (quando b é diferente de 1, i. e., isométrica) pode ser transformada logaritmicamente em uma função linear (Equações 3 e 4) e ser utilizada na determinação do b através da inclinação da reta.

$$\ln y = \ln a + b \ln x \quad (3)$$

$$\ln TM = \ln a + b \ln MC \quad (4)$$

No entanto, devido à grande diversidade de formas dos organismos, é difícil caracterizar a MC com tendo um comportamento fisiológico linear. Segundo Barbosa (2007), na alometria é comum usar a MC como uma variável independente (x) por ela ser uma grandeza que pode ser facilmente medida na maioria dos organismos, sua medida pode ser feita com bastante precisão e seu intervalo de variação pode variar consideravelmente. Como variável dependente (y), característica de plantas e animais, destacam-se a taxa metabólica basal (TMB), a frequência cardíaca (FC) do organismo em repouso, o tempo de vida de um organismo, o raio da aorta e do tronco das árvores, a duração do ciclo de respiração nas aves e nos mamíferos e o tempo para alcançar a puberdade nas aves e nos mamíferos.

Baseado na minimização de energia e na geometria fractal da rede de distribuição de nutrientes, West *et al.* (1997) retomou o debate em relação ao valor correto do expoente alométrico correspondente a taxa metabólica basal (TMB) ao derivarem a lei dos $\frac{3}{4}$ (BARBOSA, 2007). Segundo West *et al.* (1997) a lei de Kleiber ($b = \frac{3}{4}$) caracteriza a TMB de quase todos os organismos, contrário a muitos pesquisadores que acreditam que a TMB é governada apenas pela lei da superfície de Rubner ($b = \frac{2}{3}$) (DODDS *et al.*, 2001; WHITE e SEYMOUR, 2003) e a outros que acreditam não existir um único valor específico de b na natureza (GLAZIER, 2005; TARTARUGA *et al.*, 2009; TARTARUGA *et al.*, 2010).

Apesar da consistente fundamentação de West *et al.* (1997), alguns problemas foram evidenciados mais tarde. Muitas variáveis e processos biológicos nas aves e nos mamíferos parecem ter expoentes aproximadamente próximos de $\frac{1}{3}$, tais como a duração do ciclo de respiração, o tempo para puberdade, entre outros (BARBOSA, 2007). Também, estudos têm demonstrado que o b , correspondente a taxa metabólica máxima (TMM), é maior do que o da TMB (WEIBEL *et al.*, 2004), além de alguns erros matemáticos e conceituais terem sido encontrados para explicar a origem do expoente $\frac{3}{4}$ da TMB, enfraquecendo a teoria proposta

por Kleiber, em 1932 (DODDS *et al.*, 2001; WEIBEL *et al.*, 2004). Por fim, TMM, determinada alometricamente, também têm sido relacionada com a temperatura corporal de animais invertebrados e organismos unicelulares (Figura 2), espécies que necessitam, assim com os vertebrados, manter a temperatura corporal constante (CALDER, 1981; GILLOOLY *et al.*, 2001), o que demonstra uma variabilidade nos resultados.

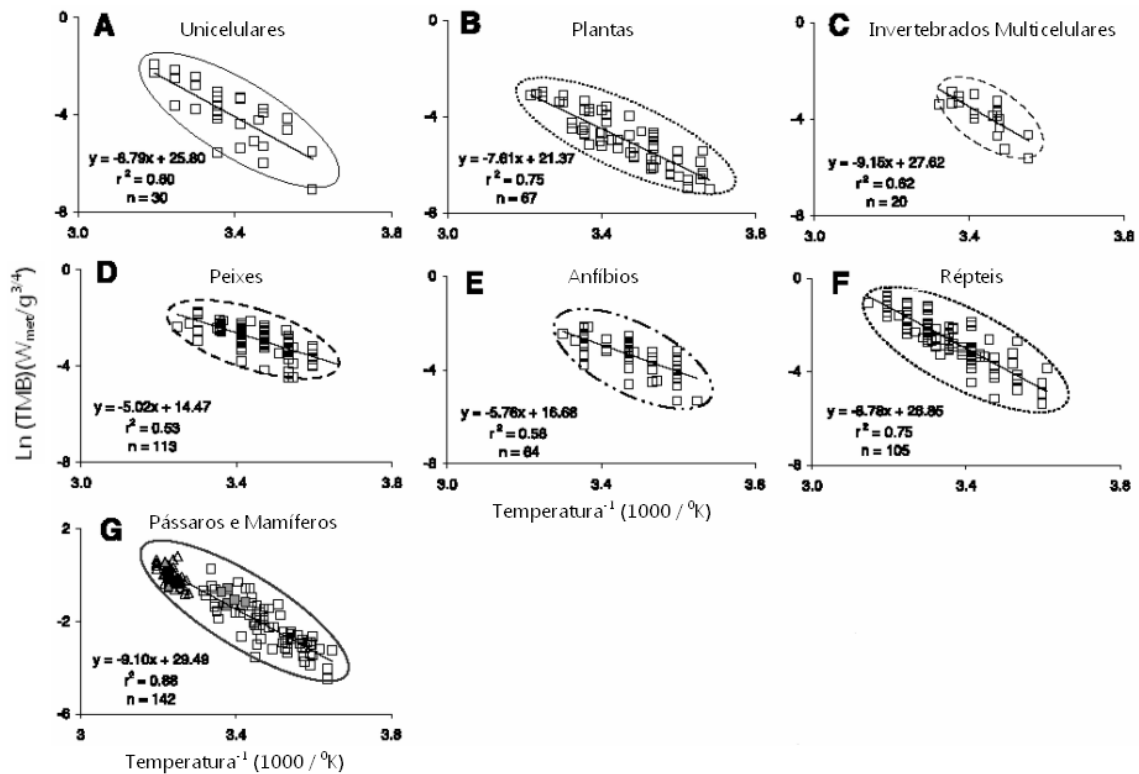


Figura 2 – Efeito da temperatura na taxa metabólica basal relativa de seres unicelulares (A), plantas (B), invertebrados multicelulares (C), peixes (D), anfíbios (E), répteis (F), aves e mamíferos (G). Pássaros (símbolos cinzas) e mamíferos (símbolos abertos) são apresentados com temperaturas normais (triângulos) e temperaturas durante a hibernação (quadrados) (GILLOOLY *et al.*, 2001).

Nos últimos anos, o interesse no estudo do metabolismo escalar tem ressurgido com novas propostas metodológicas e análises científicas. West *et al.* (1997) e Banavar *et al.* (1999) propuseram que a escala metabólica pode ser entendida com bases na limitação de suprimentos e/ou nos processos fisiológicos que contribuem para a regulação da TM, como também proposto mais tarde por Darveau *et al.* (2002), Hochachka *et al.* (2003), entre outros (Figura 3). Apesar disso, Dodds *et al.* (2001) analisando a TM de 391 espécies de mamíferos e de 398 espécies de aves, verificaram que as bases científicas para rejeitar o b de $\frac{2}{3}$ proposto por Rubner (1883), correspondente a relação entre TM e superfície corporal, eram insuficientes. White e Seymour (2003), investigando o comportamento da TM de 619 espécies de mamíferos de diferentes temperaturas corporais, verificaram relações significativas entre

TM e temperatura corporal correspondentes a $\frac{2}{3}$. Dodds *et al.* (2001) e White e Seymour (2003) destacaram que a metodologia empregada para a determinação da TM, da superfície e da temperatura corporal podem influenciar no valor do expoente.

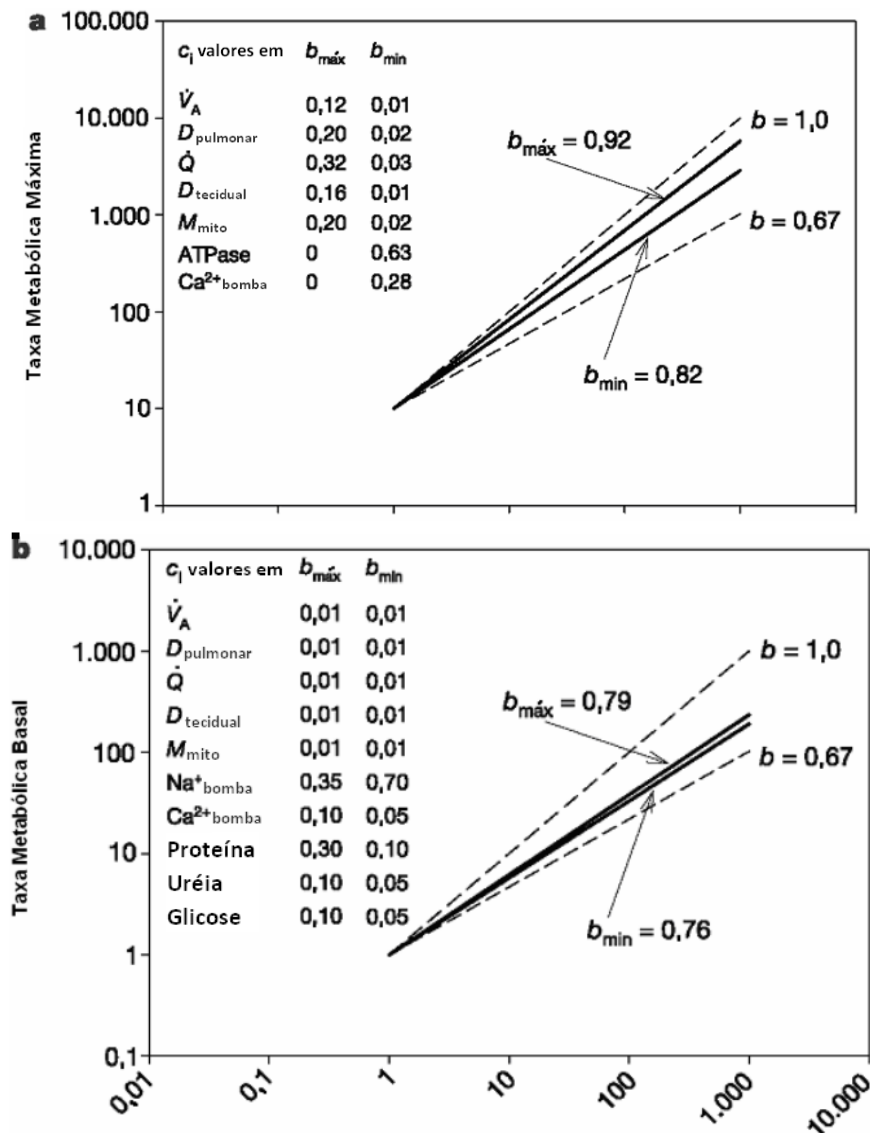


Figura 3 – Estimativas de expoentes alométricos (b) correspondentes a taxa metabólica máxima (a) e a taxa metabólica basal (b) de mamíferos (DARVEAU *et al.*, 2002). *Nota:* ventilação alveolar (V_A), difusão pulmonar ($D_{pulmonar}$), débito cardíaco (Q), difusão tecidual capilar-mitocôndria ($D_{tecdual}$), metabolismo citosólico e mitocondrial (M_{mito}), hidrólise de adenosina trifosfato (ATPase), bomba de Cálcio (Ca^{+2}_{bomba}) e bomba de Sódio (Na^{+}_{bomba}).

Uma outra proposta de determinação do b que surgiu na década de 90 corresponde a filogenética. A TMB de mamíferos tem sido filogeneticamente determinada por diversos pesquisadores (GARLAND e CARTER, 1994). De acordo com Symonds e Elgar (2002) o b depende tanto da evolução fisiológica como do modelo de regressão adotado. Essa afirmação

corroborar com os estudos de Tieleman e Williams (2000) e Frappell *et al.* (2001). Os defensores do método filogenético argumentam que as análises envolvendo regressões e medidas entre diferentes espécies (interespecíficas) falham devido a suposição de que medidas pontuais, que representam cada espécie, são estatisticamente independentes. Isso se deve ao fato de que mesmo diferentes espécies de animais, por exemplo aves, são descendentes de um mesmo ancestral em comum. Análises de medidas interespecíficas são, dessa forma, potencialmente confundidas com relações filogenéticas (SUAREZ *et al.*, 2004).

Embora opiniões difiram em relação a qual b deva ser adotado em estudos investigatórios da TM, percebe-se que existe um longo caminho a ser percorrido na busca do melhor expoente. Entretanto, os estudos até então desenvolvidos demonstram que, independente do expoente a ser adotado, o mesmo possui forte sensibilidade a MC e a superfície corporal, conforme verificado por Rubner (1883), e Kleiber (1932), o que torna necessário o desenvolvimento de novos estudos cujo objetivo seja o de esclarecer melhor as relações entre TM, MC e superfície corporal.

2.1.1. TAXA METABÓLICA EM SITUAÇÃO BASAL

Segundo os modelos propostos por Banavar *et al.* (1999) e West *et al.* (1997; 1999), grandes animais, como baleias, apresentam menores taxas metabólicas basais relativas em comparação a pequenos animais, como por exemplo, ratos, cuja MC é aproximadamente 10^7 menor que a das baleias. Provavelmente essas menores taxas metabólicas basais relativas verificadas em grandes animais são consequências de uma limitação na oferta de substratos e/ou de O_2 para as células pelo sistema circulatório, o que torna pequenos animais mais perspicazes em comparação a grandes animais. Apesar disso, sabe-se que a demanda de substrato ou de O_2 de mamíferos aumenta significativamente (até 10 vezes em relação ao repouso) em situação de exercício (HOPPELER e WEIBEL, 2000), além de influenciar na recuperação da TMB pós-exercício. Esse aumento pode ser ainda maior dependendo do condicionamento cardiorrespiratório (JONES e LINDSTEDT, 1993).

Os valores da TMB do corpo inteiro representam a soma do metabolismo de diversos órgãos internos, inclusive o coração, que executa trabalho mecânico próprio, e outros, tais como o cérebro, o fígado e os rins, que despendem energia devido, principalmente, a biossíntese e ao transporte de substâncias pelas membranas (Figura 4) (SUAREZ *et al.*, 2004). Por esse motivo, músculos locomotores apresentam baixas taxas de ressíntese e hidrólise de adenosina trifosfato (ATP) e baixo consumo de O_2 , além de pouco influenciar na TMB. Dessa forma, é plausível acreditar que a TMB pode ser compreendida em termos escalares da MC e das taxas metabólicas internas de cada órgão (WANG *et al.*, 2001).

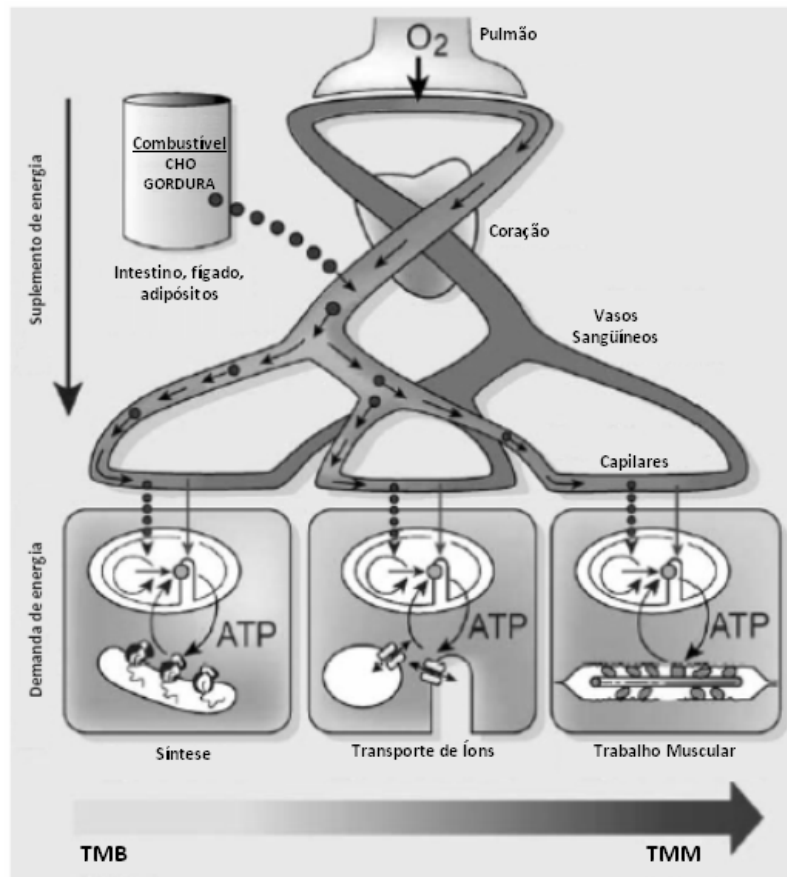


Figura 4 – Aumento da taxa metabólica resultante do transporte de substâncias pelas membranas (WEIBEL, 2002). *Nota:* carboidrato (CHO) e adenosina trifosfato (ATP).

Mas o que determina a TM de um órgão? Um estudo bioquímico referente a esta questão pode ser iniciado com a idéia de que para uma determinada célula os mecanismos regulatórios da homeostasia devem garantir a harmonização entre a síntese e a hidrólise de ATP. A hidrólise de ATP pode mudar de acordo com as condições fisiológicas, influenciando nas taxas de síntese e permitindo a manutenção das concentrações intracelulares de ATP. Em condições aeróbias, a maioria do ATP sintetizado é decorrente da fosforilação oxidativa mitocondrial. Dessa forma, a taxa de consumo de O_2 pode representar a soma das taxas correspondentes a respiração mitocondrial. Nas últimas três décadas, a Teoria do Controle Metabólico tem emergido juntamente com as investigações relacionadas a regulação do metabolismo (THOMAS *et al.*, 1997).

Um conceito básico que tem emergido é que todas as etapas do processo estão envolvidas na regulação do metabolismo. No entanto, até 35 anos atrás, antes que a Teoria do Controle Metabólico ganhasse aceitação, a hipótese de que as taxas metabólicas celulares ou de um organismo poderiam ser reguladas pelas limitações de transportes de substratos e/ou O_2 apenas poderia ser refutada pelo metabolismo celular. Este é o motivo pelo qual o processo de hidrólise de ATP tem um papel importante no controle da síntese de ATP (ATKINSON, 1968).

Na época, acreditava-se que esse controle ocorria através de mecanismos como a modulação alostérica da atividade fosfofrutoquinase pelos nucleotídeos (MANSOUR e AHLFORS, 1968).

De acordo com Couture e Hulbert (1995), a TM celular *in vitro* diminui com o aumento da massa e em vários órgãos a capacidade de transporte de íons na membrana celular diminui com o aumento da massa. As atividades das enzimas glicolíticas, expressas em grama de massa tecidual, aumentam enquanto as atividades das enzimas oxidativas diminuem com o aumento da massa em músculos locomotores de mamíferos (EMMETT e HOCHACHKA, 1981). A densidade do volume mitocondrial e/ou a área de superfície diminui com o aumento da massa no cérebro, fígado, rins, coração e músculo esquelético, resultando uma diminuição da capacidade de utilização e síntese de ATP (HOPPELER *et al.*, 1984).

Todos os relatos mencionados anteriormente demonstram que massas de órgãos e a TM variam especificamente (WANG *et al.*, 2001). Dessa forma, procedimentos alométricos podem contribuir na análise da TM corporal de diversos órgãos em situação basal, sendo estes influenciado pelas massas específicas e corporais. Na tabela 1 são apresentados quaisquer expoentes alométricos resultantes da relação entre TMB e MC verificados em alguns estudos realizados com aves e mamíferos, citados por Barbosa (2007).

Tabela 1. Expoentes alométricos resultantes de relações entre TMB e MC de diversos estudos.

Expoente	Grupo	Intervalo de MC	Referências
0,664	398 aves	< 10 g - 100,0 kg	(DODDS <i>et al.</i> , 2001)
0,668	357 pequenos mamíferos	< 10 g - 10,0 kg	(DODDS <i>et al.</i> , 2001)
0,710	391 mamíferos	< 10 g - 3,67 ton.	(DODDS <i>et al.</i> , 2001)
0,669	126 aves	5,0 g - 100,0 kg	(MCKECHNIE e WOLF, 2004)
0,712	626 mamíferos	2,4 g - 3,67 ton.	(SAVAGE <i>et al.</i> , 2004)
0,737	52 mamíferos	2,4 g - 3,67 ton.	(SAVAGE <i>et al.</i> , 2004)

Nota: taxa metabólica basal (TMB), massa corporal (MC).

2.1.2. TAXA METABÓLICA EM SITUAÇÃO MÁXIMA

Um dos primeiros pesquisadores a investigar o comportamento alométrico de mamíferos em situação de máximo esforço foi Taylor *et al.* (1981). Eles investigaram o comportamento da TMM de mamíferos domésticos e selvagens, obtendo expoentes alométricos de 0,790 e 0,855, respectivamente. Quando os dois grupos foram analisados juntos o *b* obtido foi de 0,809. Anos mais tarde, Taylor *et al.* (1988) e Weibel *et al.* (1991) adicionaram novas espécies na análise anterior e obtiveram o valor de 0,86 para os dois grupos juntos. A partir destes estudos, outros surgiram para corroborar com estudos da TMM (BARBOSA, 2007). Por exemplo, Hinds *et al.* (1993), que mediram a TMM de 30 espécies de mamíferos induzida pela exposição a baixa temperatura e pelo exercício e obtiveram valores de 0,772 e 0,882, respectivamente.

Bishop (1999), em um estudo sobre o consumo máximo de oxigênio ($VO_{2máx}$) de aves e mamíferos, concluiu que as características estruturais do sistema cardiovascular podem ter sido desenvolvidas para a TMM. De acordo com o autor, a diferença no *b* da TMM é devida a diferentes adaptações da estrutura cardiovascular e respiratória das espécies de animais. Além

disso, Bishop definiu um organismo padrão no qual a massa do coração deve ser 1% da MC e com a concentração de hemoglobina igual a 15 g para 100 mililitros de sangue (BARBOSA, 2007), demonstrando que a TMM das aves e dos mamíferos ajusta-se ao padrão escalar com b de $0,88 \pm 0,02$, com $r = 0,999$. Já White e Seymour (2005) encontraram um b de $0,87 \pm 0,05$ para a TMM dos mamíferos e Niven e Scharlemann (2005) estudaram a TMM de insetos e encontraram um b de 0,86.

De forma geral, a natureza logarítmica da equação alométrica sugere que a escala da TM esteja relacionada com algumas propriedades fractais do organismo. Dois modelos universais têm sido propostos com base em estudos vasculares, mitocondriais e capilares. De acordo com esses modelos, a TMM deve escalar com $\text{kg}^{3/4}$ (WEIBEL e HOPPELER, 2005), diferentemente do b de $0,872 (\pm 0,029)$ verificado por Weibel *et al.* (2004) quando investigadas 34 espécies de mamíferos *eutherian* com MC variando entre 7g e 500 kg. Quando esses mamíferos foram separados em espécies “atléticas” e “não-atléticas” eles encontraram expoentes alométricos de $0,942 \pm 0,024$ e $0,849 \pm 0,024$, respectivamente. De acordo com Weibel *et al.* (2004), a TMM está linearmente relacionado com a quantidade de mitocôndria e capilares do organismo, bem como as suas áreas de superfície. Isso, conseqüentemente, confirma a teoria inicial de que o modelo fractal poderia descrever melhor o comportamento escalar da TMM, refutando, dessa forma, o argumento da relação entre TMM e $\text{kg}^{3/4}$ e sugerindo, inclusive, que a energia necessária para a locomoção poderia estar relacionada à $\text{kg}^{7/8}$.

Especificamente em seres-humanos, Tartaruga *et al.* (2008), relacionando o $\text{VO}_{2\text{máx}}$ e o limiar anaeróbio (LA), determinado pela ventilação e lactacidemia, de 10 corredores e 15 remadores de rendimento, verificaram boas correlações apenas entre o $\text{VO}_{2\text{máx}}$ e o LA quando este foi determinado exclusivamente pela ventilação, independente da utilização de expoentes alométricos específicos (0,67; 0,73; 0,75) e da massa corporal magra na normalização da MC. Os autores concluíram que a normalização alométrica pode ser adotada em estudos de variáveis fisiológicas quando estas forem determinadas a partir de comportamentos ventilatórios. A tabela 2 apresenta os expoentes alométricos específicos advindos da relação entre TMM e MC dos corredores e remadores, bem como de outros mamíferos menores, estes citados por Barbosa (2007).

Tabela 2. Expoentes alométricos resultantes de relações entre TMM e MC de diversos estudos.

Expoente	Grupo	Intervalo de MC	Referências
0,772	12 mamíferos marsupiais	15,3 g - 2,03 kg	(HINDS <i>et al.</i> , 1993)
0,789	19 mamíferos theria	15,3 g - 2,03 kg	(HINDS <i>et al.</i> , 1993)
0,882	9 mamíferos marsupiais	16,7 g - 4,84 kg	(HINDS <i>et al.</i> , 1993)
0,880	9 mamíferos e 6 aves	5,0 g - 500,0 kg	(BISHOP, 1999)
0,828	21 mamíferos	2,4 g - 3,67 ton.	(SAVAGE <i>et al.</i> , 2004)
0,872	34 mamíferos	7,4 g - 500,0 kg	(WEIBEL <i>et al.</i> , 2004)
0,991	10 corredores	52,4 - 71,0 kg	(TARTARUGA <i>et al.</i> , 2010)
0,690	15 remadores	76,3 - 90,7 kg	(TARTARUGA <i>et al.</i> , 2010)

Nota: taxa metabólica máxima (TMM), massa corporal (MC).

Utilizando a mesma amostra do estudo citado anteriormente, agora determinando o b específico de cada grupo, Tartaruga *et al.* (2010) verificaram valores correspondentes a 0,99 para corredores e de 0,69 para remadores. Eles justificaram a diferença ao percentual de gordura corporal (11,9% e 13,6%, respectivamente). Além disso, a predição do desempenho em ambos os grupos foi alterada sem e com a utilização do b , permitindo afirmar que a escala alométrica pode ser uma boa alternativa, também, na comparação do condicionamento físico de atletas de diferentes modalidades esportivas.

2.1.3. TAXA METABÓLICA NA LOCOMOÇÃO

A TM durante exercício submáximo também pode ser predita alometricamente (SUAREZ *et al.*, 2004). Na locomoção terrestre, o trabalho muscular desenvolvido por passo escala com a MC, enquanto que o número de passos por unidade de distância é inversamente proporcional a $MC^{1/3}$. Isso pode ser verificado em estudos analisando corridas de animais bípedes e quadrúpedes (SCHMIDT-NIELSEN, 1975). É importante perceber que a TM, predita alometricamente, aparentemente independe do substrato energético utilizado durante a locomoção, o que justifica o desenvolvimento de mais estudos investigando a referida predição com base em outras variáveis independentes diferentes das propostas por West *et al.* (1997; 1999) e Banavar *et al.* (1999).

Da mesma forma, têm se verificado que a frequência de nado de peixes, em velocidade ótima, diminui com o aumento da MC, assim como o custo de transporte (C_{transp}), calculado em $\text{ml.kg}^{-1}.\text{m}^{-1}$ (VIDELER e WEIHS, 1982). Em contrapartida, outros autores tem demonstrado que a velocidade relativa, expressa com base no tamanho corporal por unidade de tempo, é tamanho-independente em animais aquáticos (SUAREZ *et al.*, 2004), contrário a animais bípedes terrestres, nos quais o número de Froude (NF) tem sido utilizado como forma de relativização da velocidade de locomoção pelo tamanho corporal (VAUGHAN e O'MALLEY, 2005). A velocidade de locomoção, a aceleração da gravidade e o comprimento de membro inferior são representados na fórmula do NF (Equação 5) por v , g e L , respectivamente.

$$NF = \frac{v}{\sqrt{g.L}} \quad (5)$$

Embora a MC, principalmente magra, se correlacione com a capacidade aeróbia, a maioria dos estudos mostra que para atividades submáximas, como a marcha, a massa corporal total se correlaciona mais com o consumo de oxigênio do que com o tamanho corporal (MILLER e BLYTH, 1955).

Datta *et al.* (1973) verificaram que era a MC de pessoas suportando cargas de 0 a 50 kg na cabeça que se correlacionava melhor com o consumo de oxigênio, desde que essa carga não fosse excessiva ou transportada em uma posição incômoda. Goldman e Lampietro (1962), mensurando o consumo de oxigênio de cinco pessoas utilizando diferentes combinações de velocidades de esteira, de inclinação e de cargas nas costas, observaram que, para uma dada velocidade e inclinação, o consumo de oxigênio por unidade de MC era semelhante. Robertson

et al. (1982) confirmaram que isso ocorria também com o transporte de cargas de até 15% da MC.

Turell *et al.* (1964) e Bloom *et al.* (1965) compararam o consumo de oxigênio durante a marcha de pessoas magras e obesas. Embora o consumo de oxigênio absoluto tenha sido maior em pessoas obesas, a relativização pela MC forneceu um resultado semelhante. Por outro lado, Myo *et al.* (1985) observaram que a previsão baseada na MC com cargas no tronco superestimava o consumo de oxigênio. O custo metabólico (C_{met}) de cargas aplicadas ao tronco com a pessoa parada de pé é praticamente zero. O valor da energia total (E_{tot}) para ficar parado é de aproximadamente $22 \text{ cal.kg}^{-1}.\text{min}^{-1}$. Em um experimento com um homem jovem com MC de 64 kg, verificou-se que o valor de E_{tot} para ficar parado de pé não se alterou de forma mensurável com 20 kg distribuídos de maneira uniforme em torno do tronco.

De forma geral, os estudos investigando a TM e/ou o consumo de oxigênio na locomoção são bem diversificados em seus achados. No entanto, independente das variáveis investigadas para a predição da TM ou do consumo de oxigênio, todos os estudos destacam a importância da alometria na predição dos valores das respectivas variáveis durante a locomoção, principalmente quando investigadas as relações da MC e do consumo submáximo de oxigênio ($VO_{2subm\acute{a}x}$) com a TM.

2.2. MECÂNICA E ENERGÉTICA DA LOCOMOÇÃO

A locomoção tem sido objeto de estudo devido a sua importância na evolução. Desde as primeiras células vivas até os animais mais complexos, como os seres humanos, todos usaram a locomoção para se deslocar pelo mundo fugindo de desastres naturais, predadores ou em busca de alimentos e água. Assim muitas espécies sobreviveram e evoluíram formando o mundo dos seres vivos como conhecemos hoje (MCMAHON, 1975).

Estudos, tanto em animais como em humanos, buscam incansavelmente decifrar os mecanismos da locomoção, como o corpo se comporta e como responde a variações da tarefa, por exemplo, durante a marcha. Diversos pesquisadores, como Cavagna *et al.* (1963; 1964), publicaram estudos referente a locomoção, fundamentando as principais pesquisas nos dias de hoje. Em um primeiro momento sistematizaram a locomoção como um mecanismo de pêndulo invertido; em seguida descreveram o comportamento do CM_c e do CM_s com o conceito físico de que o W_{tot} corresponde a variação de energia, considerando que a posição dos mesmos varia ao longo do passo.

Em um terceiro momento, após descreverem o comportamento do trabalho mecânico por meio de referências “externas”, o que foi denominado de W_{ext} , Cavagna *et al.* (1977) integraram na locomoção o conceito de E_f , sendo esta a capacidade de produzir W_{tot} com o menor C_{met} possível. O W_{int} , derivado do teorema da energia cinética total de um sistema (teorema de Köning), já havia sido descrito por Fenn, em 1930, e formalizado por Cavagna e Kaneko (1977). Entretanto, somente mais tarde sua relação com o W_{tot} foi preconizada (WILLEMS *et al.*, 1995). Mas a grande associação proposta pelos trabalhos citados anteriormente é de que o W_{tot} , calculado com base no comportamento do CM_c e do CM_s de cada segmento corporal é resultante de fenômenos fisiológicos e mecânicos corporais.

A partir disso, passou-se a investigar o comportamento do CM_c e do CM_s de cada segmento corporal de animais de várias espécies e de seres humanos, em diferentes condições de tarefa, como por exemplo, em diferentes velocidades, em diferentes inclinações e em diferentes ambientes (MINETTI *et al.*, 1993; 1994). Da mesma forma, estudos foram desenvolvidos com o objetivo de calcular o W_{tot} através da predição matemática do W_{int} e W_{ext} (CAVAGNA *et al.*, 1991; MINETTI, 1998; NARDELLO *et al.*, 2011) buscando-se, assim, entender melhor o funcionamento das estruturas internas como músculos, tendões e articulações, bem como os fenômenos que envolvem a contração muscular e as alterações metabólicas durante a locomoção.

2.2.1. A VARIAÇÃO DE ENERGIA

Estudos com seres humanos e animais propõem que a caminhada se dá através do mecanismo do pêndulo invertido, quando os membros atuam de forma simultânea e oposta (CAVAGNA *et al.*, 1977; GRIFFIN *et al.*, 2004). Durante esse processo o CM_c se desloca e há trocas constantes de energia. A energia potencial gravitacional (EPG) e a energia cinética (EC) comportam-se de forma inversa (CAVAGNA *et al.*, 1977).

Para quadrúpedes, esse mecanismo se parece mais com dois pêndulos invertidos: um deles nos membros anteriores e outro nos membros posteriores. No entanto, esse mecanismo ainda não está muito bem esclarecido, pois, aparentemente, as energias não variam como nos bípedes e, por existirem quatro apoios e não somente dois, há maior balanço do CM_c durante a locomoção em quadrúpedes (GRIFFIN *et al.*, 2004). Lee *et al.* (2008) citam ainda a possibilidade de contatos simultâneos e assimetrias de membros individuais durante a locomoção podendo não ser o duplo pêndulo o melhor modelo para explicar esta locomoção.

As variações de energias podem estar relacionadas ao W_{tot} realizado durante a locomoção (CAVAGNA *et al.*, 1963; CAVAGNA e MARGARIA, 1966; CAVAGNA *et al.*, 1977). Assim, se medida a variação da posição do CM_c no lado direito e no lado esquerdo, teremos curvas que representam a EPG e a EC do corpo em questão, sendo a variação destas o W_{ext} . Pode-se ainda verificar as variações dos centros de massas segmentares durante o movimento em relação ao CM_c , o que representa o comportamento do W_{int} de cada segmento corporal, resultante, na sua grande maioria, da contração de vários grupos musculares, da força passiva dos tecidos, da energia metabólica despendida, enfim, de todos os processos que acontecem no organismo e que resultam no deslocamento do corpo (CAVAGNA *et al.*, 1977; WILLEMS *et al.*, 1995; GRIFFIN *et al.*, 2004).

Estudos sobre a locomoção de diversos animais, em especial pássaros, mamíferos bípedes e quadrúpedes, revelam que o CM_c atinge uma maior amplitude de deslocamento vertical quando a marcha é desenvolvida em velocidades lentas a moderadas, o que resulta na suposição de que durante a locomoção a velocidade de deslocamento influencia no comportamento do CM_c e, conseqüentemente, no W_{ext} e, logo, no W_{tot} (CAVAGNA *et al.*, 1976; HEGLUND *et al.*, 1982; MINETTI *et al.*, 1999).

Heglund *et al.* (1982) relacionando as energias advindas da movimentação de cada CM_s e do CM_c verificaram que a E_{tot} de um animal é resultante, em qualquer instante da marcha, da

soma da EPG, da EC e da energia potencial elástica (EPE), assumindo, no entanto, que a soma dessas energia ocorre apenas se não houver transferências de energia entre os membros corporais. Além disso, o trabalho dos músculos antagonistas que atuam para frear ou estabilizar o movimento é descartado por ser pequeno em relação a E_{tot} (HEGLUND *et al.*, 1982).

Após o conhecimento das variações de energia, passou-se a investigar as causas dessas variações, como por exemplo, as contrações musculares e o armazenamento de energia. Ao descrever as variações de energia como compostas por trabalhos mecânicos positivos e negativos, passou-se a relacionar o trabalho mecânico positivo com a contração concêntrica – dependente unicamente da energia metabólica – e o trabalho mecânico negativo com a contração excêntrica – colaboração das estruturas elásticas (CAVAGNA *et al.*, 1963; CAVAGNA *et al.*, 1968). A partir dessa observação passou-se a considerar que os mecanismos elásticos (aquelas que oferecem resistência mecânica ao alongamento sem custo energético – força passiva) da estrutura músculo-tendinosa dos membros inferiores são importantes na determinação do C_{transp} , correspondente ao dispêndio de oxigênio advindo dos músculos em função da distância percorrida normalizada pela MC (CAVAGNA, 2010).

Estudos sobre os efeitos da MC no C_{transp} têm demonstrado que durante a locomoção a demanda metabólica aumenta linearmente com a MC (ABE *et al.*, 2008), diferente do aumento curvilíneo que ocorre com o aumento da velocidade de deslocamento, independente da MC (BASTIEN, 2005). Especificamente na corrida, Kram e Taylor (1990) estudaram em cinco espécies de mamíferos e propuseram três equações com o objetivo de prever o C_{transp} durante a corrida. Segundo os autores, o gasto energético está relacionado a um custo para manter o peso corporal durante o tempo disponível para geração de força. Esse tempo para gerar força estaria associado ao tempo de aplicação do passo no solo. Eles afirmaram que a maior parte da força produzida pelos músculos é uma ação em oposição à gravidade. Além disso, o volume muscular ativo produziria a mesma quantidade de força sem considerar a velocidade, ou o tamanho do animal. Por fim, os músculos trabalhariam de forma similar à relação força-velocidade, sem considerar a velocidade da corrida e o tamanho do animal.

Baseado nesse último pressuposto, afirmou-se que animais menores requerem fibras mais rápidas em altas velocidades, pois eles possuem um menor comprimento de membros inferiores. Assim, os tempos para aplicação de força também diminuiriam. Os autores concluíram que a hipótese estava certa, visto que seus resultados mostraram que o consumo de energia metabólica é influenciado pelo tempo para aplicação de força e o custo para suportar o peso corporal em mamíferos abrangendo entre 30g a 140kg.

2.2.2. O TRABALHO MECÂNICO

A análise do movimento corporal durante a locomoção tem despertado o interesse de diversos pesquisadores da área, principalmente no que se refere ao estudo da mecânica da locomoção humana e ao cálculo do trabalho mecânico desenvolvido (WILLIAMS e CAVANAGH, 1983). Particularmente, o W_{tot} tem sido tradicionalmente determinado através da soma do W_{ext} e do W_{int} (CAVAGNA e KANEKO, 1977; SAIBENE e MINETTI, 2003).

O W_{ext} correspondente ao trabalho necessário para elevar e acelerar o CM_c em relação ao meio externo (SAIBENE e MINETTI, 2003), tem sido investigado em diferentes condições e populações (CAVAGNA *et al.*, 1983; MINETTI *et al.*, 1993; SCHEPENS *et al.*, 2001; SAIBENE e MINETTI, 2003). Este tem sido calculado com base no comportamento da E_{tot} em função do tempo, de acordo com a Equação 6 (CAVAGNA *et al.*, 1976; WILLEMS *et al.*, 1995; SAIBENE e MINETTI, 2003), através de procedimentos cinemáticos, dinamometria e/ou dinâmica inversa.

$$E_{\text{tot}} = \text{EPE} + \text{EC} \quad (6)$$

Já os movimentos recíprocos dos segmentos do corpo que não afetam a trajetória do CM_c (CAVAGNA *et al.*, 1964; MINETTI, 1998) são, em grande parte, provocados por forças internas do corpo. Consequentemente, o trabalho associado com as mudanças de energia interna corresponde ao W_{int} (WILLEMS *et al.*, 1995; MINETTI, 1998; MINETTI *et al.*, 1999). O mesmo pode ser calculado através de procedimentos cinemáticos e com base em parâmetros antropométricos de cada segmento corporal (SCHEPENS *et al.*, 2001).

Historicamente, o conceito de W_{int} foi introduzido por Fenn, em 1930, para corridas em altas velocidades (CAVAGNA *et al.*, 1964) e reformulado por Cavagna e Kaneko (1977). O W_{int} derivado do teorema de Köning, referente a E_{tot} de um sistema, diz que a EC de um sistema de partículas corresponde a EC associada ao movimento do centro de massa do sistema e a EC associada ao movimento do CM de cada partícula do sistema em relação ao CM geral (CAVAGNA e FRANZETTI, 1986). Portanto, em um sistema multi-segmentar, a energia cinética total pode ser dividida em dois diferentes componentes: o primeiro referente ao comportamento do CM_c em relação ao meio ambiente (W_{ext}) e o segundo referente ao comportamento de cada CM_s em relação ao CM_c (W_{int}). Consequentemente, o interesse da biomecânica no W_{int} reside na capacidade de considerar a aceleração de cada segmento, como ocorre na locomoção humana (caminhada e corrida, particularmente), quando os membros são movimentados quase que simetricamente em relação ao CM_c (MINETTI *et al.*, 1993; MINETTI, 1998).

Para o W_{int} somente a EC se faz necessária, pois ela é influenciada diretamente pela velocidade com que os membros executam o movimento em relação ao CM_c . Já o W_{ext} é o resultado da soma entre EC e EPG, quando a altura em que se encontra o centro de gravidade, associado à sua velocidade de deslocamento durante um ciclo de passada, são variáveis que influenciam no comportamento do W_{ext} (HEGLUND e TAYLOR, 1988). De acordo com Ferris *et al.* (1998) e Saibene e Minetti (2003), o comportamento das energias (EC e EPG) ocorrem de forma simultânea durante a locomoção, entretanto, de maneira distinta quando comparado a caminhada com a corrida.

Dessa forma, o W_{tot} pode ser determinado pela soma dos trabalhos internos e externos, conforme a Equação 7.

$$W_{\text{tot}} = W_{\text{int}} + W_{\text{ext}} \quad (7)$$

A corrida é caracterizada como uma série de impactos contra o solo (*bouncing*). Durante a primeira metade da fase de contato do pé com o solo, parte da E_{tot} é transformada em EPE através do alongamento de tendões e tecidos conjuntivos (elementos não-contráteis) (CAVAGNA, 2010). Esta primeira parte é representada pelos valores negativos da força de reação do solo anteroposterior. Já na segunda metade da fase de contato, essa força passa a apresentar valores positivos, quando parte da energia armazenada na primeira fase é transferida ao sistema através do encurtamento do tendão (SAIBENE e MINETTI, 2003). Esse comportamento de reutilização de energia mecânica através do armazenamento da EPE (*bouncing*) é peculiar durante a corrida, trote e saltos (CAVAGNA *et al.*, 1964).

Em relação às variáveis comprimento e frequência de passada, maiores velocidades de corrida resultam em aumento da frequência de passada e aumento e/ou manutenção do comprimento de passada para um mesmo sujeito, pois grandes velocidades requerem maiores potências mecânicas para manutenção da movimentação do CM_c (Figura 5) (NUMMELA *et al.*, 2007). Com o aumento da velocidade, ocorre uma diminuição da amplitude vertical do CM_c devido a uma diminuição do impulso vertical e um aumento da frequência de passada devido ao aumento da potência mecânica para acelerar os membros em relação ao CM_c . Assim, é possível manter o mesmo trabalho mecânico por mais tempo como forma de minimização de energia (CAVAGNA *et al.*, 1988).

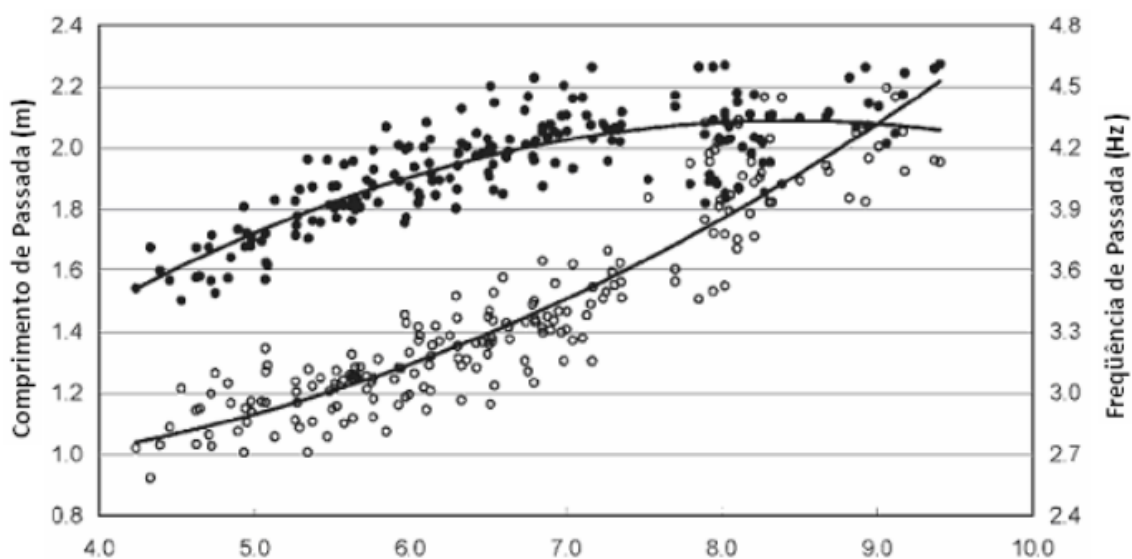


Figura 5 – Respostas do comprimento (círculos pretos) e da frequência (círculos brancos) de passada decorrentes do aumento da velocidade de corrida (NUMMELA *et al.*, 2007).

Portanto, o W_{tot} realizado durante a locomoção, subdividido em W_{int} e W_{ext} , sofre forte influência do comprimento e da frequência de passada durante a marcha. Uma forma de otimizar o W_{tot} consiste na diminuição da frequência de passada e com isso, também no W_{int} , sem que ocorra queda na velocidade durante a corrida. Para isso, torna-se necessário o aumento do comprimento de passada (TARTARUGA *et al.*, 2003; TARTARUGA *et al.*, 2004; CAVAGNA *et al.*, 2008). Dessa forma, variáveis mecânicas têm ganhado destaque por

demonstrarem relação com a minimização de energia durante a locomoção (KYROLAINEN *et al.*, 2001; CAVAGNA *et al.*, 2008).

2.2.3. A EFICIÊNCIA MECÂNICA

Durante a locomoção o corpo está sujeito a trocas de energias. No entanto, essas trocas acontecem de forma equilibrada, sendo a soma da EC com a EPG um valor muito próximo de zero durante o passo (MARGARIA, 1968; CAVAGNA *et al.*, 1977). Especificamente é produzido trabalho mecânico positivo e, em seguida, a mesma quantidade de trabalho mecânico negativo (MARGARIA, 1968).

A Ef, entendida como a capacidade de produzir trabalho com pouca energia metabólica ou trabalho metabólico, é representada pela razão entre as energias mecânica e metabólica (Equação 8). Segundo Margaria (1968), ao caminhar no plano os trabalhos mecânicos positivos e negativos se equivalem durante um ciclo da marcha. Quando uma quantidade igual de trabalho mecânico positivo e negativo é desenvolvida, a Ef é de aproximadamente 0,3 ou 30 %.

$$E_f = W_{tot} \cdot W_{met}^{-1} \quad (8)$$

Vários são os fatores que influenciam a Ef. A velocidade de locomoção, o tamanho corporal e a inclinação do terreno são alguns deles. Segundo Heglund *et al.* (1982) a Ef aumenta com o aumento da velocidade e atinge comportamento próximo a um platô em animais de pequeno porte. A velocidade de início do platô é muito próxima a velocidade ótima de locomoção, o que segundo Wickler *et al.* (2000), é determinada por características musculoesqueléticas específicas que podem resultar em um menor C_{met} , conseqüentemente uma melhor Ef para uma mesma velocidade. Wickler *et al.* (2000) também apresentam resultados que indicam relação positiva entre a velocidade ótima e C_{transp} , sendo que em alyce, quando o C_{transp} é maior, a velocidade ótima passa a ser mais baixa. Resultados de Minetti *et al.* (1995) reforçam essa idéia demonstrando que os humanos escolhem uma frequência de passada que minimiza o W_{int} e o W_{ext} , diminuindo a energia metabólica. A Figura 6 apresenta dados de Ef em relação a velocidades de animais e seres humanos.

De acordo com Heglund *et al.* (1982) animais de pequeno porte gastam mais energia metabólica em menores velocidades. Já animais de médio-grande porte gastam menos energia metabólica e chegam a maiores velocidades, principalmente, devido ao tamanho corporal. O comportamento da E_{tot} se mantém. Animais maiores alcançam maiores velocidades, mas a E_{tot} é semelhante em todos os animais, considerando a MC de cada um.

Essa característica pode ser explicada por Close (1972) que afirma que a capacidade de produção de força diminui com o aumento da velocidade, conforme a curva clássica de força-velocidade de Hill (1938). Assim, torna-se necessário o recrutamento de fibras musculares com mais ciclos acoplamento/desacoplamento de actina e miosina, pontes cruzadas em maior quantidade e mais rápidas e, conseqüentemente, mais consumo de energia metabólica. Músculos equivalentes apresentam pontes cruzadas mais eficientes em animais menores quando comparados a animais maiores (CLOSE, 1972).

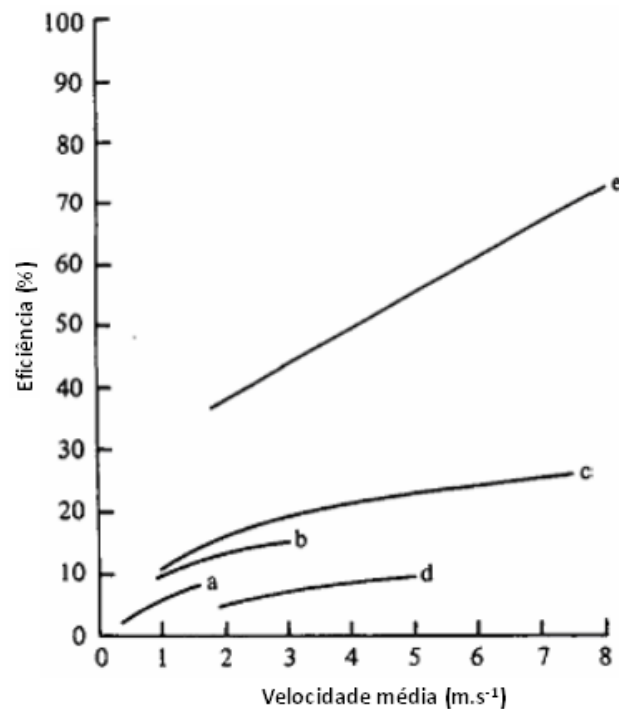


Figura 6 – Valores de Ef em relação a velocidades médias de locomoção para: a) codornas (± 43 g); b) gambás (± 107 g); c) cachorros (± 5 kg); d) perus ($\pm 6,4$ kg); e) humanos (± 70 kg) (HEGLUND *et al.*, 1982).

Diversos estudos têm demonstrado que a Ef durante a locomoção aumenta com o tamanho corporal e a velocidade. No entanto, essas observações não têm sido confirmadas em estudos investigando isoladamente determinados grupos musculares (HILL, 1938). Têm-se verificado, de forma global, que a Ef em seres humanos, cangurus e pôneis é de aproximadamente 70% (CAVAGNA *et al.*, 1977; HEGLUND *et al.*, 1982; TAYLOR, 1985). Já em músculos isolados, o valor é de aproximadamente 25% (HILL, 1938). Essas diferenças podem estar relacionadas a capacidade de armazenamento de EPE de cada músculo envolvido durante a locomoção.

Rome *et al.* (1990) demonstraram que a velocidade máxima de encurtamento de fibras musculares oxidativas de mamíferos é proporcional a $MC^{-0,18}$. Este valor exponencial é semelhante a relação entre frequência de passada e $MC^{-0,16}$ (HEGLUND e TAYLOR, 1988), o que demonstra que a eficiência muscular pode ser semelhante entre pequenos e grande animais. Da mesma forma, Kram e Taylor (1990) têm demonstrado que a velocidade máxima de encurtamento de fibras musculares oxidativas pode estar relacionada diretamente a Ef na locomoção. Estes observaram a existência de uma relação inversa entre velocidade máxima de encurtamento de fibras musculares oxidativas e tempo de contato com o solo (fase de suporte), demonstrando que grandes animais podem apresentar maiores Ef em decorrência de maiores tempos de contatos com o solo e menores frequências de passos.

Evidências substanciais indicam que a EPE é armazenada e liberada dos tecidos conectivos e contráteis durante a locomoção (ALEXANDER, 1991). Além de grandes animais armazenarem mais EPE que pequenos animais, eles apresentam uma maior capacidade de utilização dessa

energia para a locomoção, o que os torna mais eficientes. Entretanto, em espécies de animais muito grandes, essa capacidade de utilização da EPE pode ser parcialmente restrita a fatores de segurança de ossos e articulações decorrentes do tamanho, resultando em uma diminuição da velocidade máxima de corrida, sobretudo, em animais acima de 50 kg (BIEWENER, 1989).

2.3. INTENSIDADE E VELOCIDADE NA LOCOMOÇÃO

O tamanho corporal afeta praticamente todas as funções fisiológicas dificultando a comparação do desempenho de animais e seres humanos (JONES e LINDSTEDT, 1993; TARTARUGA *et al.*, 2008; TARTARUGA *et al.*, 2009; TARTARUGA *et al.*, 2010). Esta dificuldade é ilustrada na Figura 7 que mostra a máxima velocidade de corrida de 148 espécies de mamíferos de diferentes tamanhos, plotada semi-logaritmicamente em função da MC. A figura 7a mostra a velocidade absoluta, em $\text{m}\cdot\text{s}^{-1}$, e a figura 7b, a velocidade relativa à quantidade de massa corporal (Q_{mc}) (JONES e LINDSTEDT, 1993), determinado pela Equação 9:

$$Q_{mc} = 24,8 MC^{1/3} \quad (9)$$

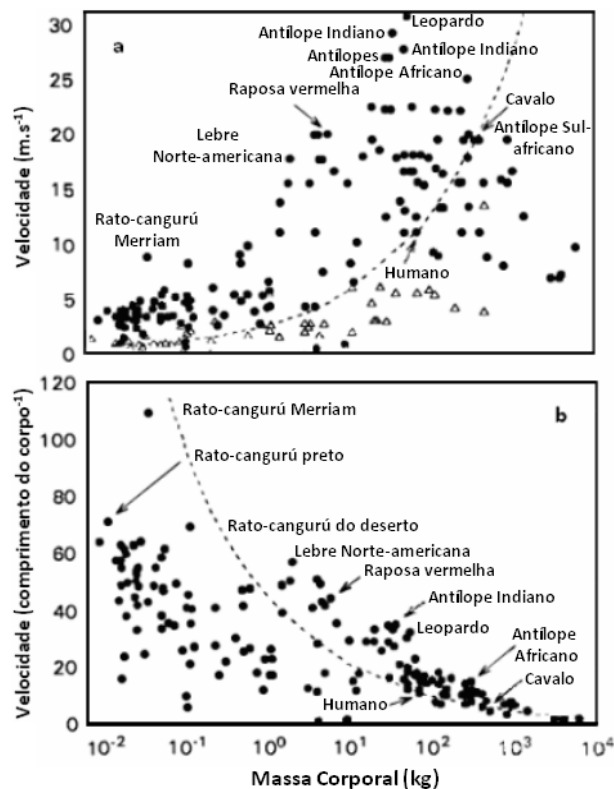


Figura 7 – Velocidades máximas (círculos pretos) de 148 espécies de mamíferos plotadas em função do logaritmo natural da MC. As linhas tracejadas representam as velocidades que mamíferos de diferentes tamanhos corporais deveriam desenvolver para obterem o mesmo desempenho que uma pessoa de 70 kg. Triângulos abertos representam a máxima velocidade aeróbica de 45 espécies de animais (JONES e LINDSTEDT, 1993).

Comparando-se a locomoção de uma chita de 55 kg e de um rato de 35 g percebe-se que a velocidade máxima de deslocamento de ambos os animais modifica-se em decorrência da forma de expressão da velocidade (absoluta ou relativa ao CM), demonstrando a importância do tamanho corporal na comparação do desempenho intra e interespécies.

Na prática esportiva, estudos têm verificado a necessidade de utilizar valores diferentes como expoentes para a determinação do percentual a ser considerado da MC. Estes valores seriam específicos para diferentes esportes (JENSEN *et al.*, 2001) e populações (GOOSEY-TOLFREY *et al.*, 2003). Neste âmbito, Saltin e Astrand (1967) afirmam que a relação entre $VO_{2m\acute{a}x}$ e MC é utilizada devido a forma de deslocamento da MC.

Jensen *et al.* (2001), analisando a relação entre $VO_{2m\acute{a}x}$ e MC de 967 atletas, correspondentes a 25 modalidades esportivas, encontraram diferentes valores de expoentes alométricos para cada modalidade esportiva analisada. Após, foi calculado um *b* médio aproximado de 0,73 para todas as modalidades, o que permitiu a criação de um *ranking* de capacidade aeróbia que foi liderado pelo ciclistas e corredores de longa distância.

A mesma análise pode ser feita em estudos de economia de movimento, como o estudo de Tartaruga *et al.* (2010), aonde foi verificado que a aplicação da escala alométrica permite que as características pessoais influenciem na predição desempenho físico, neste caso, de remadores de rendimento (Tabela 3).

Tabela 3. Valores de $VO_{2subm\acute{a}x}$ de 15 remadores de rendimento reportados tradicionalmente e alometricamente (TARTARUGA *et al.* 2010).

REMO			
$VO_{2sum\acute{a}x}$ ($ml\ kg^{-1}\ min^{-1}$)		$VO_{2sum\acute{a}x}$ ($ml\ kg^{0,69}\ min^{-1}$)	
Remador 1	36,54	Remador 1	146,49
Remador 2	37,18	Remador 3*	147,41
Remador 3	37,61	Remador 4*	149,78
Remador 4	37,76	Remador 2*	150,71
Remador 5	38,48	Remador 5	152,76
Remador 6	39,07	Remador 7*	153,29
Remador 7	39,96	Remador 6*	154,42
Remador 8	40,44	Remador 8	157,32
Remador 9	40,92	Remador 10*	160,94
Remador 10	41,17	Remador 15*	162,57
Remador 11	42,09	Remador 14*	163,60
Remador 12	42,32	Remador 13*	163,68
Remador 13	42,60	Remador 12*	164,51
Remador 14	42,80	Remador 9*	170,30
Remador 15	42,91	Remador 11*	172,78

A Figura 8 mostra a plotagem logarítmica de velocidades médias em função de tempos de duração de corridas de curtas, médias e longas distâncias de seres-humanos, cachorros e cavalos, onde o ângulo de inclinação das retas representa o metabolismo aeróbio de cada uma das espécies (JONES e LINDSTEDT, 1993).

No entanto, a velocidade máxima de corrida não é a única variável relacionada ao máximo desempenho físico, que pode ser definido como sendo a habilidade de manter uma máxima potência durante um período máximo de tempo. Os mecanismos fisiológicos que limitam a potência durante o exercício de alta intensidade e longa duração são similares entre as diferentes espécies de mamíferos. Esses mecanismos estão relacionados a duração da

atividade física, ao recrutamento de fibras musculares, as concentrações de ácido láctico, glicogênio muscular e hepático (JONES e LINDSTEDT, 1993).

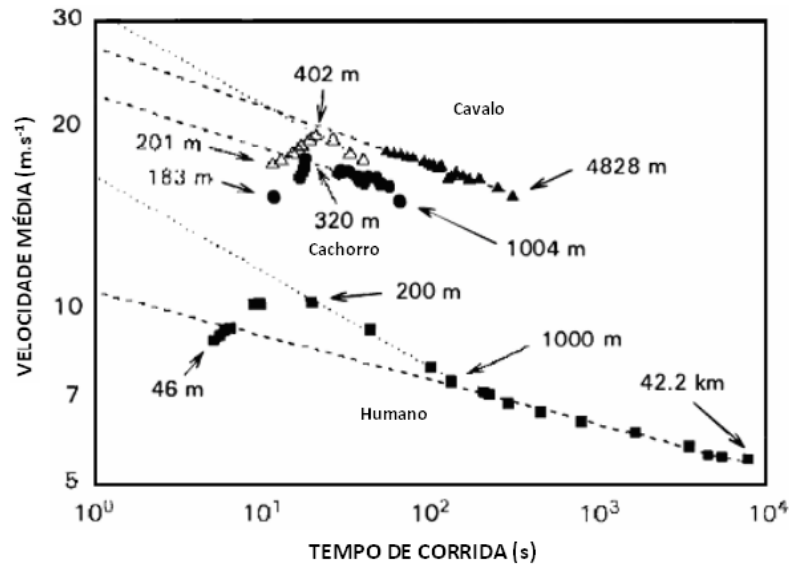


Figura 8 – Plotagem logarítmica da velocidade média em função do tempo de corrida para diferentes distâncias de humanos (quadrados), cachorros (círculos) e cavalos (triângulos). Linhas tracejadas escuras relacionam-se a potências metabólicas advindas predominantemente do metabolismo aeróbio de longas distâncias de corrida e linhas tracejadas claras relacionam-se a potências metabólicas advindas predominantemente do metabolismo anaeróbio de curtas distâncias de corrida (JONES e LINDSTEDT, 1993).

Percebe-se, pelas inclinações das retas, que quanto maior a duração do exercício, menor é o metabolismo absoluto. Da mesma forma, percebe-se que o metabolismo, principalmente entre seres-humanos e cavalos, é semelhante. Já os a das equações das retas representam as velocidades máximas previstas que correspondem aos picos de força que cada uma das espécies investigadas podem produzir em um pequeno intervalo de tempo (próximo de 1 s) ou ao período de um ciclo acto-miosínico predito por $MC^{0,25}$ (LINDSTEDT *et al.*, 1985).

A capacidade aeróbia pode ser avaliada em termos absolutos, como a velocidade que um animal pode manter em um determinado período de tempo, ou em termos relativos, como a relação entre velocidade média e desempenho. Como o C_{transp} é predito com a $MC^{-0,3}$ (TAYLOR *et al.*, 1970; TAYLOR e HEGLUND, 1982), parece que o C_{met} é maior em pequenos animais, e que esse custo é influenciado pela máxima velocidade de locomoção.

2.4. VARIÁVEIS DETERMINANTES DO DESEMPENHO LOCOMOTOR

O desempenho locomotor tem sido relacionado com a quantidade de força e a potência mecânica que um animal pode gerar e sustentar. Estas variáveis estão relacionadas, principalmente, aos mecanismos mecânicos e energéticos musculares, ao comportamento de

variáveis biomecânicas da corrida (principalmente o comprimento e frequência de passada) e ao custo energético da locomoção (JONES e LINDSTEDT, 1993).

A força muscular de animais vertebrados é advinda, principalmente, das estruturas contráteis (interação actina e miosina). Hill (1950) verificou que o trabalho muscular realizado a cada contração pode ser constante em todos os músculos de mamíferos, conseqüentemente, todos os mamíferos poderiam ser capazes de desenvolverem a mesma velocidade de corrida.

Em relação ao comprimento e a frequência de passada, variáveis influenciadoras da velocidade, diversos estudos têm sido desenvolvidos na busca de uma melhor compreensão da influência destas no W_{tot} e na relação com a MC (HOGBERG, 1952; HEGLUND e TAYLOR, 1988; MINETTI *et al.*, 1995). Jones e Lindstedt (1993) (Figura 7b) têm verificado que a velocidade máxima de mamíferos, quando relativizada com o tamanho corporal, possui uma relação alométrica com a massa MC, e que mamíferos com massas corporais próximas de 50 kg tendem a apresentarem deslocamentos mais rápidos. Schmidt-Nielsen (1975) verificou que se mamíferos de diferentes tamanhos possuem comprimentos de passadas geometricamente similares, as velocidades máximas apresentarão fortes relações com os valores de $MC^{0,16}$. Entretanto, mamíferos não possuem comprimentos de passadas geometricamente similares devido as amplitudes articulares pois, grandes mamíferos apresentam baixas amplitudes angulares em suas articulações em comparação a pequenos animais (MCMAHON, 1975; BIEWENER, 1989). Contudo, este padrão geral de dependência de tamanho é muito variado. Os membros de velozes corredores, como por exemplo o leopardo, movimenta-se através de grandes amplitudes angulares articulares em comparação da predição em função de seu tamanho corporal. A razão da velocidade máxima de corrida diminuir com o aumento da MC acima de 50 kg pode estar relacionada a postura e as mudanças na marcha que ocorrem para uma maior prevenção de lesões ao nível ósseo, muscular e de tendão (BIEWENER, 1982 e 1989), demonstrando que a compreensão do comprimento e da frequência de passada são primordiais na busca de um melhor entendimento do desempenho locomotor (JONES e LINDSTEDT, 1993).

Por fim, Taylor e colaboradores (TAYLOR *et al.*, 1980; HEGLUND *et al.*, 1982; TAYLOR *et al.*, 1982; TAYLOR, 1985; HEGLUND e TAYLOR, 1988), investigando a relação entre MC, C_{met} e trabalho muscular durante a corrida, verificaram que o C_{met} na corrida é diretamente proporcional a velocidade e a $MC^{-0,3}$, o que permite concluir que o custo energético por passo (ou passada) por kg pode sofrer influência da MC, diretamente relacionada ao tamanho corporal, para marchas similares, aumentando com o aumento da velocidade de corrida.

2.5. CAPACIDADE AERÓBICA

Tem sido amplamente reconhecido que o tamanho corporal, principalmente a MC, e o metabolismo basal são alometricamente relacionados, ou seja, a TMB possui forte relação com $MC^{0,7}$. Da mesma forma, a relação exponencial entre a TMM e a MC também tem sido reportada em estudos realizados com mamíferos (JONES e LINDSTEDT, 1993).

De acordo com Powers e Howley (2012), a capacidade aeróbica consiste na capacidade que um organismo tem de captar, transportar e utilizar o oxigênio para produção de energia muscular. Sabe-se que quanto maior a MC envolvida no movimento maior será o $\dot{V}O_{2\text{máx}}$.

Atualmente, é comum relativizar o consumo de oxigênio pela MC total. No entanto, O tamanho corporal, principalmente a MC, afeta praticamente todas as funções fisiológicas dificultando a comparação do desempenho de animais e seres humanos (JONES e LINDSTEDT, 1993; TARTARUGA *et al.*, 2008; TARTARUGA *et al.*, 2009; TARTARUGA *et al.*, 2010). Um exemplo pode ser verificado na Figura 9, que demonstra a relação logarítmica linear entre $\dot{V}O_{2\text{máx}}$ a massa e MC das mesmas 37 espécies de mamíferos.

De forma geral, pequenos mamíferos possuem grandes capacidades aeróbicas específicas do que grandes animais mamíferos. Entretanto, animais com menos de 50 kg de MC podem apresentar capacidades aeróbicas específicas quatro vezes mais do que a prevista para seus tamanhos. Da mesma forma, animais com aproximadamente 50 kg de MC podem apresentar três vezes menos capacidades aeróbicas específicas que a prevista. Isso demonstra que o tamanho corporal possui um papel importante na capacidade aeróbica máxima de animais mamíferos e que mais estudos devem ser desenvolvidos para um maior detalhamento no assunto.

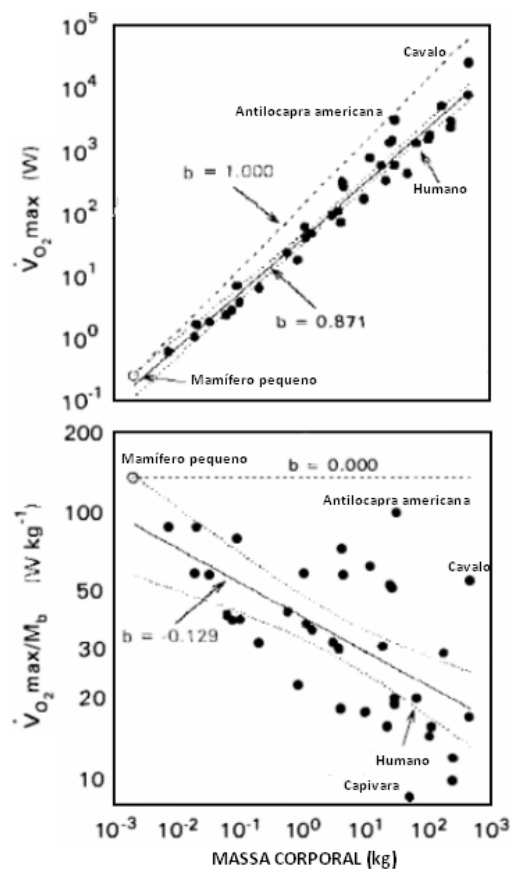


Figura 9 – Logaritmo do $\dot{V}O_{2\text{máx}}$ (calculado para $1 \text{ mL O}_2 \cdot \text{s}^{-1} = 20,1 \text{ W}$) em função do logaritmo da MC de 37 espécies de mamíferos. No painel superior, o $\dot{V}O_{2\text{máx}}$ é apresentado em termos absolutos e, no painel inferior, em termos relativos a MC (JONES e LINDSTEDT, 1993).

2.6. CAPACIDADE ANAERÓBICA

A especificidade do exercício físico é, possivelmente, um dos princípios mais utilizados na planificação do treinamento esportivo, e o estabelecimento do perfil bioenergético das modalidades esportivas está entre as principais formas de caracterização da solicitação metabólica imposta por essas tarefas. Acredita-se que, durante o exercício cíclico e de alta intensidade, o metabolismo aeróbio exerce a sua predominância a partir do trigésimo segundo (SPENCER e GASTIN, 2001), logo o consumo de oxigênio pode ser utilizado como marcador desse sistema bioenergético.

Por outro lado, nos instantes iniciais do exercício de alta intensidade e curta duração, a sustentação dos processos que requerem energia durante a contração muscular ocorre preferencialmente por vias que não necessitam de oxigênio, denominadas de metabolismo anaeróbio. O metabolismo anaeróbio, por sua vez, é subdividido nos componentes alático e láctico, os quais se referem respectivamente à hidrólise dos estoques dos fosfatos de alta energia (ATP e fosfato de creatina - CP) e à degradação parcial da glicose, que resulta na formação de lactato (GASTIN, 2001). Logo, ao se analisar a relação entre o tempo e a intensidade dos exercícios, supõe-se que a capacidade anaeróbia, a qual pode ser definida como a quantidade total de energia transferida pelos metabolismos anaeróbios durante a execução de um exercício de alta intensidade (GASTIN e LAWSON, 1994), desempenha papel fundamental em algumas tarefas contínuas (SPENCER e GASTIN, 2001; DUFFIELD *et al.*, 2004) e intermitentes (SPRIET, 1992).

Por outro lado, diferentemente do metabolismo aeróbio, a mensuração da capacidade anaeróbia é de difícil realização, devido à dificuldade de acesso aos marcadores fisiológicos e/ou mecânicos que melhor a representem. Esse fato implica diretamente na impossibilidade de se estabelecer um teste-padrão ouro e na baixa precisão das técnicas atuais (GASTIN, 2001). Diversos instrumentos têm sido utilizados na tentativa de mensurá-la, sendo os principais o testes de força-velocidade monoarticular, o salto vertical a subida em degraus, o teste ergométrico e a análise da cinética do oxigênio nos instantes iniciais ou finais do esforço (GASTIN, 2001). No entanto, existe uma tendência de se conceituar o máximo déficit acumulado de oxigênio (MAOD) como o método mais aceitável para avaliação do metabolismo anaeróbio (GREEN e DAWSON, 1993), sobretudo pela fundamentação teórica que o envolve (GASTIN e LAWSON, 1994).

2.6.1. MÁXIMO DÉFICIT DE OXIGÊNIO ACUMULADO

O Máximo Déficit de Oxigênio Acumulado (MAOD), inicialmente proposto por Medbo *et al.* (1988), vem sendo considerado uma medida bastante confiável da capacidade anaeróbia (SCOTT *et al.*, 1991; GASTIN e LAWSON, 1994). A sua determinação consiste em estabelecer, inicialmente, uma relação linear individual entre a demanda de oxigênio e a intensidade de exercício. Para isso, os autores propõem cargas submáximas que variam de 35 a 100% do $VO_{2máx}$, sendo necessárias de 10 a 20 sessões de cargas submáximas com duração de 10 minutos, com a demanda de oxigênio para cada intensidade de exercício calculada como a

média dos dois últimos minutos de esforço. O procedimento proposto para sua determinação dificulta a sua aplicação, mas os autores julgam ser necessários vários esforços, pois ocorre uma considerável variação interindividual de, aproximadamente, 16% na Ef (NAKAMURA e FRANCHINI, 2006).

Posteriormente, para a quantificação do MAOD, são propostas cargas retangulares supra-máximas na faixa de 110 a 125% da velocidade no $VO_{2\text{máx}}$ que induzem a exaustão em torno de dois a sete minutos de exercício. As cargas menores que dois minutos não possibilitam a manifestação completa do MAOD e as cargas maiores que dez minutos dependem diretamente da motivação do atleta, podendo ocasionar erros significativos na medida. Assim, estabelecendo a demanda de oxigênio acumulada em testes supra-máximos como o produto da demanda de oxigênio e o tempo de exercício realizado até a exaustão, o MAOD é a diferença entre a demanda e o consumo de oxigênio acumulado no teste. Para melhor detalhamento, ver Figura 10.

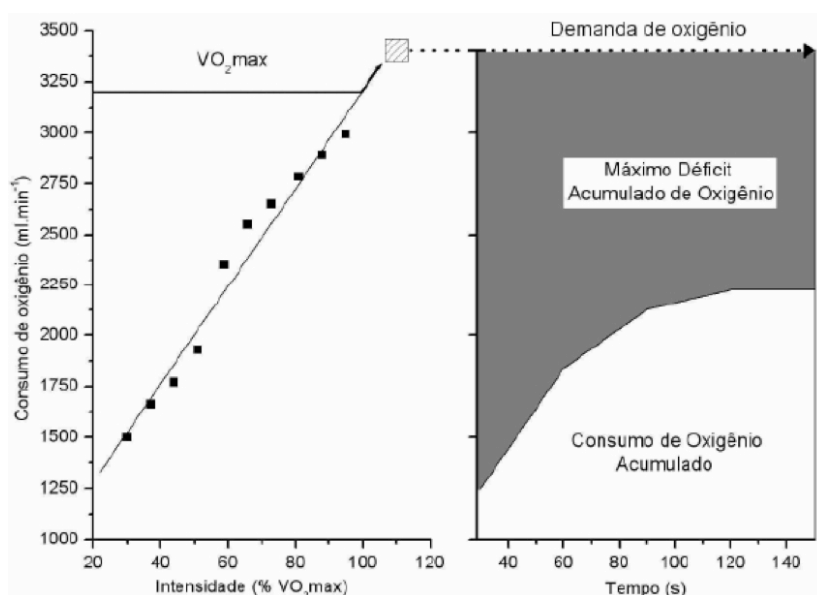


Figura 10 – Exemplo gráfico dos princípios metodológicos empregados na determinação do Déficit Máximo Acumulado de O_2 (MEDBO *et al.*, 1988).

Medbo *et al.* (1988) estabelece o procedimento que adota um valor de intercepto y igual para todos os indivíduos, permitindo que seja realizada uma relação linear mais confiável entre demanda de oxigênio e intensidade de exercício com um número menor de cargas submáximas, sendo elas próximas ao $VO_{2\text{máx}}$. Desta maneira, viabilizando uma maior praticidade na aplicação do MAOD, com estimativas de capacidade anaeróbia próximas ao modelo original. Outros autores (SCOTT *et al.*, 1991; HILL, 1996; HILL *et al.*, 2002), visando melhorar a aplicabilidade do MAOD, desenvolveram metodologias alternativas (p. e., modificando o tempo de exercício das intensidades submáximas e os percentuais de cargas) para sua determinação, sendo realizadas em esteira ou cicloergômetro.

O método proposto por Medbo *et al.* (1988), mesmo com sua baixa praticidade, parece ser o procedimento fisiológico mais confiável para a determinação da capacidade anaeróbia (NAKAMURA e FRANCHINI, 2006). No presente estudo de Medbo *et al.* (1988), os autores realizaram o MAOD com três sujeitos em duas condições, hipóxia e normóxia, para confirmar que a variável de capacidade anaeróbia é independente do metabolismo aeróbio. Assim, os resultados mostraram que o $VO_{2máx}$ em hipóxia reduziu de maneira significativa e o MAOD não apresentou diferença significativa em ambas condições. Com estes resultados, os pesquisadores concluem que o método é válido para avaliação da capacidade anaeróbia. Entretanto, a validade do método, para quantificar a capacidade anaeróbia é, todavia, questionada (BANGSBO, 1996). Desde o ponto de vista fisiológico, a velocidade máxima de corrida depende essencialmente da capacidade anaeróbia e a velocidade submáxima de corrida, predominantemente aeróbica, depende, em parte, da força e da resistência muscular, podendo esta última ser quantificada alometricamente (JARIC *et al.*, 2002).

2.7. CONCLUSÃO

Desde os estudos de Rubner (1883) e Kleiber (1932), a alometria vem sendo utilizada na biologia evolutiva como uma maneira de compreender melhor a relação da TM com a massa e a superfície corporal. Diversos estudos com animais de diferentes tamanhos e, mais recentemente, com seres humanos, têm demonstrado que a aplicação de modelos não-lineares (alométricos) podem melhor representar o comportamento exponencial da TM de diferentes animais e seres-humanos.

Algumas teorias foram desenvolvidas com o objetivo de justificar o comportamento exponencial da TM e, conseqüentemente, a aplicação de modelos alométricos. Dentre essas teorias, destacaram-se as relações da TM com a superfície corporal (RUBNER, 1883), com a MC (KLEIBER, 1932; 1947), com os aspectos geométricos de órgãos e tecidos (WEST *et al.*, 1997) e com a filogenética (GARLAND e CARTER, 1994) e a temperatura corporal (GILLOOLY *et al.*, 2001). Por muitos anos, inclusive, se ponderou que as relações da TM com a massa e a superfície corporal fossem alométricas, inclusive com expoentes específicos ($kg^{3/4}$ e $kg^{2/3}$, respectivamente); duas teorias “em cheque” em termos de especificidade, e que também foram apuradas em seres-humanos.

Especificamente no âmbito esportivo, desde os primeiros estudos de Hill na década de 30, é de consenso entre os especialistas da área que os principais fatores fisiológicos que predizem o desempenho em modalidades esportivas integradas por provas de meia e longa distância (p. e., corrida, ciclismo e natação) são o consumo de oxigênio e o LA (BASSETT e HOWLEY, 2000; FOSTER e LUCILA, 2007; NUMMELA *et al.*, 2007), sendo o primeiro relativizado pela MC total para fins de comparação entre sujeitos. Entretanto, apesar da forte relação existente entre consumo de oxigênio e desempenho, a referida afinidade vem sofrendo algumas críticas. Estudos investigando a predição do desempenho desportivo através do consumo de oxigênio de sujeitos morfológicamente heterogêneos têm demonstrado a necessidade de relativizar esse parâmetro com valores concernentes a MC, diferentes da MC total (BRISWALTER *et al.*,

1996, WEST *et al.*, 1997; JENSEN *et al.*, 2001; DARVEAU *et al.*, 2002; TARTARUGA *et al.*, 2009; 2010), adotando-se, dessa forma, a alometria.

Em relação a marcha humana, é de consenso que os parâmetros mecânicos (i. e., W_{int} , W_{ext} e W_{tot}) e a E_f também influenciam na locomoção. Por muitos anos, a locomoção humana foi utilizada para fugir de desastres naturais, predadores ou em busca de alimentos e água, sendo hoje, fundamental no cotidiano e no desempenho físico (CAVAGNA, 2010). Diversos pesquisadores, como Cavagna *et al.* (1963; 1964), publicaram estudos clássicos referentes a locomoção, fundamentando as principais pesquisas nos dias de hoje. Sabe-se hoje, que a caminhada e a corrida podem ser descritos através de dois modelos matemáticos: o pêndulo invertido e o sistema massa-mola, respectivamente. Porém, assim como tem ocorrido com as variáveis fisiológicas preditoras do desempenho de provas esportivas de meia e longa distância a locomoção também vêm sendo investigada alometricamente, uma averiguação que já foi realizada em animais por alguns autores, como p. e., Schmidt-Nielsen (1975), no qual constatou que se mamíferos de diferentes tamanhos possuírem comprimentos de passadas geometricamente similares, as velocidades máximas apresentarão fortes relações com os valores de $MC^{0,16}$. Da mesma forma, Taylor *et al.* (1980; 1982), investigando a relação entre MC, C_{met} e trabalho muscular durante a corrida, sendo estes últimos determinantes da E_f , verificaram que o C_{met} na corrida é diretamente proporcional a velocidade e a $MC^{-0,3}$, o que permite concluir que o custo energético por passo (ou passada) por kg pode sofrer influência da MC, diretamente relacionada ao tamanho corporal, para marchas similares, aumentando com o aumento da velocidade de corrida.

Embora o consumo de oxigênio, especificamente a ECO, e a E_f serem fortemente relacionadas com o desempenho em corridas de meia e longa-distância, ambas influenciadas pelas capacidades aeróbica e anaeróbica, além de que o comportamento exponencial da TM pode ser melhor representado por relações alométricas com a massa e a superfície corporal, nenhum estudo têm sido verificado investigando a influência da escala alométrica no comportamento da ECO e da E_f e, conseqüentemente, nas relações destas para com o desempenho esportivo, especificamente.

2.8. REFERÊNCIAS BIBLIOGRÁFICAS

1. Abe T, Kearns CF, Sato Y (1985). Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. *J Appl Physiol*, 100:1460-1466.
2. Alexander RM (1991). Energy-saving mechanisms in walking and running. *J Exp Biol*, 160:55-69.
3. Atkinson DE (1968). Citrate and the citrate cycle in the regulation of energy metabolism. *Biochem Soc Symp*, 27:23-40.
4. Banavar JR, Maritan A, Rinaldo A (1999). Size and form in efficient transportation networks. *Nature*, 399:130-132.

5. Bangsbo J (1996). Oxygen deficit: a measure of the anaerobic energy production during intense exercise? *Can J Appl Physiol*, 21:350-363.
6. Barbosa LA (2007). Leis da escala alométrica para as taxas metabólicas interespecíficas e para cadeias alimentares. *Tese de Doutorado*. Universidade Federal de Minas Gerais.
7. Bassett DR, Howley ET (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc*, 32:70-84.
8. Bastien GJ, Willems PA, Schepens B, Heglund NC. (2005). Effect of load and speed on the energetic cost of human walking. *Eur J Appl Physiol*, 94:76-83.
9. Biewener AA (1982). Bone strength in small mammals and bipedal birds: do safety factors change with body size? *J Exp Biol*, 98:289-301.
10. Biewener AA (1989). Scaling body support in mammals: limb posture and muscle mechanics. *Science*, 245:45-48.
11. Bishop CM (1999). The maximum oxygen consumption and aerobic scope of birds and mammals: getting to the heart of the matter. *Proc Biol Sci*, 266:2275-2281.
12. Bloom WL, Azar G, Clark J, MacKay JH (1965). Comparison of metabolic changes in fasting obese and lean patients. *Ann N Y Acad Sci*, 131:623-631.
13. Brisswalter J, Legros P, Durand M (1996). Running economy, preferred step length correlated to body dimensions in elite middle distance runners. *J Sports Med Phys Fitness*, 36:7-15.
14. Calder WA, 3rd (1981). Scaling of physiological processes in homeothermic animals. *Annu Rev Physiol*, 43:301-322.
15. Cavagna GA (2010). Symmetry and asymmetry in bouncing gaits. *Symmetry*, 2:1270-1321.
16. Cavagna GA, Dusman B, Margaria R (1968). Positive work done by a previously stretched muscle. *J Appl Physiol*, 24:21-32.
17. Cavagna GA, Franzetti P (1986). The determinants of the step frequency in walking in humans. *J Physiol*, 373:235-242.
18. Cavagna GA, Franzetti P, Fuchimoto T (1983). The mechanics of walking in children. *J Physiol*, 343:323-339.
19. Cavagna GA, Franzetti P, Heglund NC, Willems P (1988). The determinants of the step frequency in running, trotting and hopping in man and other vertebrates. *J Physiol*, 399:81-92.
20. Cavagna GA, Heglund NC, Taylor CR (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *Am J Physiol*, 233:243-261.
21. Cavagna GA, Kaneko M (1977). Mechanical work and efficiency in level walking and running. *J Physiol*, 268:467-481.

-
22. Cavagna GA, Legramandi MA, Peyre-Tartaruga LA (2008). Old men running: mechanical work and elastic bounce. *Proc Biol Sci*, 275:411-418.
 23. Cavagna GA, Margaria R (1966). Mechanics of walking. *J Appl Physiol*, 21:271-278.
 24. Cavagna GA, Saibene FP, Margaria R (1963). External work in walking. *J Appl Physiol*, 18:1-9.
 25. Cavagna GA, Saibene FP, Margaria R (1964). Mechanical work in running. *J Appl Physiol*, 19:249-256.
 26. Cavagna GA, Thys H, Zamboni A (1976). The sources of external work in level walking and running. *J Physiol*, 262:639-657.
 27. Cavagna GA, Willems PA, Franzetti P, Detrembleur C (1991). The two power limits conditioning step frequency in human running. *J Physiol*, 437:95-108.
 28. Close RI (1972). Dynamic properties of mammalian skeletal muscles. *Physiol Rev*, 52:129-97.
 29. Conley DL, Krahenbuhl GS (1980). Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc*, 12:357-360.
 30. Couture P, Hulbert AJ (1995). Relationship between body mass, tissue metabolic rate, and sodium pump activity in mammalian liver and kidney. *Am J Physiol*, 268:641-650.
 31. Coyle EF (1995). Integration of the physiological factors determining endurance performance ability. *Exerc Sport Sci Rev*, 23:25-63.
 32. Daniels J, Oldridge N, Nagle F, White B (1978). Differences and changes in VO₂ among young runners 10 to 18 years of age. *Med Sci Sports*, 10:200-203.
 33. Darveau CA, Suarez RK, Andrews RD, Hochachka PW (2002). Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature*, 417:166-170.
 34. Datta SR, Chatterjee BB, Roy BN (1973). The relationship between energy expenditure and pulse rates with body weight and the load carried during load carrying on the level. *Ergonomics*, 16:507-513.
 35. Dodds PS, Rothman DH, Weitz JS (2001). Re-examination of the "3/4-law" of metabolism. *J Theor Biol*, 209:9-27.
 36. Duffield R, Dawson B, Goodman C (2004). Energy system contribution to 100-m and 200-m track running events. *J Sci Med Sport*, 7:302-313.
 37. Emmett B, Hochachka PW (1981). Scaling of oxidative and glycolytic enzymes in mammals. *Respir Physiol*, 45:261-272.
 38. Farrell PA, Wilmore JH, Coyle EF, Billing JE, Costill DL (1979). Plasma lactate accumulation and distance running performance. *Med Sci Sports*, 11:338-344.

39. Ferris DP, Louie M, Farley CT (1998). Running in the real world: adjusting leg stiffness for different surfaces. *Proc Biol Sci*, 265:989-994.
40. Foster C, Lucia A (2007). Running economy: the forgotten factor in elite performance. *Sports Med*, 37:316-319.
41. Frappell PB, Hinds DS, Boggs DF (2001). Scaling of respiratory variables and the breathing pattern in birds: an allometric and phylogenetic approach. *Physiol Biochem Zool*, 74:75-89.
42. Frost G, Bar-Or O, Dowling J, Dyson K (2002). Explaining differences in the metabolic cost and efficiency of treadmill locomotion in children. *J Sports Sci*, 20:451-461.
43. Garland T, Jr., Carter PA (1994). Evolutionary physiology. *Annu Rev Physiol*, 56:579-621.
44. Gatin PB (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med*, 31:725-741.
45. Gatin PB, Lawson DL (1994). Variable resistance all-out test to generate accumulated oxygen deficit and predict anaerobic capacity. *Eur J Appl Physiol Occup Physiol*, 69:331-336.
46. Gillooly JF, Brown JH, West GB, Savage VM, Charnov EL (2001). Effects of size and temperature on metabolic rate. *Science*, 293:2248-2251.
47. Glazier DS (2005). Beyond the 3/4-power law: variation in the intra- and interspecific scaling of metabolic rate in animals. *Biol. Rev.*, 80:611-662.
48. Goldman RF, Iampietro PF (1962). Energy cost of load carriage. *J Appl Physiol*, 17:675-676.
49. Goosey-Tolfrey VL, Batterham AM, Tolfrey K (2003). Scaling behavior of VO₂peak in trained wheelchair athletes. *Med Sci Sports Exerc*, 35:2106-2111.
50. Green S, Dawson B (1993). Measurement of anaerobic capacities in humans. Definitions, limitations and unsolved problems. *Sports Med*, 15:312-327.
51. Griffin TM, Main RP, Farley CT (2004). Biomechanics of quadrupedal walking: how do four-legged animals achieve inverted pendulum-like movements? *J Exp Biol*, 207:3545-3558.
52. Heglund NC, Fedak MA, Taylor CR, Cavagna GA (1982). Energetics and mechanics of terrestrial locomotion. IV. Total mechanical energy changes as a function of speed and body size in birds and mammals. *J Exp Biol*, 97:57-66.
53. Heglund NC, Taylor CR (1988). Speed, stride frequency and energy cost per stride: how do they change with body size and gait? *J Exp Biol*, 138:301-318.
54. Hill AV (1938). The heat of shortening and the dynamic constants of muscle. *Proc R Soc Lond B Biol Sci*, 126:136-195.
55. Hill AV (1950). The dimensions of animals and their muscular dynamics. *Sci. Prog.*, 38:209-230.

56. Hill DW (1996). Determination of accumulated O₂ deficit in exhaustive short-duration exercise. *Can J Appl Physiol*, 21:63-74.
57. Hill DW, Davey KM, Stevens EC (2002). Maximal accumulated O₂ deficit in running and cycling. *Can J Appl Physiol*, 27:463-478.
58. Hinds DS, Baudinette RV, MacMillen RE, Halpern EA (1993). Maximum metabolism and the aerobic factorial scope of endotherms. *J Exp Biol*, 182:41-56.
59. Hochachka PW, Darveau CA, Andrews RD, Suarez RK (2003). Allometric cascade: a model for resolving body mass effects on metabolism. *Comp Biochem Physiol A Mol Integr Physiol*, 134:675-691.
60. Hogberg P (1952). How do stride length and stride frequency influence the energy-output during running? *Arbeitsphysiologie*, 14:437-441.
61. Hollmann W (2001). 42 years ago--development of the concepts of ventilatory and lactate threshold. *Sports Med*, 31:315-320.
62. Hoppeler H, Lindstedt SL, Claassen H, Taylor CR, Mathieu O, Weibel ER (1984). Scaling mitochondrial volume in heart to body mass. *Respir Physiol*, 55:131-137.
63. Hoppeler H, Weibel ER (2000). Structural and functional limits for oxygen supply to muscle. *Acta Physiol Scand*, 168:445-456.
64. Ingham SA, Whyte GP, Pedlar C, Bailey DM, Dunman N, Nevill AM (2008). Determinants of 800-m and 1500-m running performance using allometric models. *Med Sci Sports Exerc*, 40:345-350.
65. Jaric S, Radosavljevic-Jaric S, Johansson H (2002). Muscle force and muscle torque in humans require different methods when adjusting for differences in body size. *Eur J Appl Physiol*, 87:304-307.
66. Jensen K, Johansen L, Secher NH (2001). Influence of body mass on maximal oxygen uptake: effect of sample size. *Eur J Appl Physiol*, 84:201-205.
67. Jones JH, Lindstedt SL (1993). Limits to maximal performance. *Annu Rev Physiol*, 55:547-569.
68. Kleiber M (1932). Body size and metabolism. *Hilgardia*, 6:315-353.
69. Kleiber M (1947). Body size and metabolic rate. *Physiol Rev*, 27:511-541.
70. Komi PV (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech*, 33:1197-1206.
71. Kram R, Taylor CR (1990). Energetics of running: a new perspective. *Nature*, 346:265-267.
72. Kusano MA, Vanderburgh PM, Bishop P (1997). Impact of body size on women's military obstacle course performance. *Biomed Sci Instrum*, 34:357-362.

73. Kyrolainen H, Belli A, Komi PV (2001). Biomechanical factors affecting running economy. *Med Sci Sports Exerc*, 33:1330-1337.
74. Kyrolainen H, Komi PV, Belli A (1995). Mechanical efficiency in athletes during running. *Scand J Med Sci Sports*, 5:200-208.
75. Lee DV, McGuigan MP, Yoo EH, Biewener AA (2008). Compliance, actuation, and work characteristics of the goat foreleg and hindleg during level, uphill, and downhill running. *J Appl Physiol*, 104:130-141.
76. Lindstedt SL, Hoppeler H, Bard KM, Thronson HA, Jr. (1985). Estimate of muscle-shortening rate during locomotion. *Am J Physiol*, 249:699-703.
77. Loftin M, Sothorn M, Trosclair L, O'Hanlon A, Miller J, Udall J (2001). Scaling VO₂ peak in obese and non-obese girls. *Obes Res*, 9:290-296.
78. Mansour TE, Ahlfors CE (1968). Studies on heart phosphofructokinase. Some kinetic and physical properties of the crystalline enzyme. *J Biol Chem*, 243:2523-2533.
79. Margaria R (1968). Positive and negative work performances and their efficiencies in human locomotion. *Int Z Angew Physiol*, 25:339-351.
80. Margaria R, Cerretelli P, Aghemo P, Sassi G (1963). Energy cost of running. *J Appl Physiol*, 18:367-370.
81. McKechnie AE, Wolf BO (2004). The allometry of avian basal metabolic rate: good predictions need good data. *Physiol Biochem Zool*, 77:502-521.
82. McMahon TA (1975). Using body size to understand the structural design of animals: quadrupedal locomotion. *J Appl Physiol*, 39:619-627.
83. Medbo JI, Mohn AC, Tabata I, Bahr R, Vaage O, Sejersted OM (1988). Anaerobic capacity determined by maximal accumulated O₂ deficit. *J Appl Physiol*, 64:50-60.
84. Mian OS, Thom JM, Ardigo LP, Narici MV, Minetti AE (2006). Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiol (Oxf)*, 186:127-139.
85. Miller AT, Blyth CS (1955). Influence of body type and body fat content on the metabolic cost of work. *J Appl Physiol*, 8:139-141.
86. Minetti AE (1998). A model equation for the prediction of mechanical internal work of terrestrial locomotion. *J Biomech*, 31:463-468.
87. Minetti AE, Ardigo OL, Reinach E, Saibene F (1999). The relationship between mechanical work and energy expenditure of locomotion in horses. *J Exp Biol*, 202:2329-2338.
88. Minetti AE, Ardigo LP, Saibene F (1993). Mechanical determinants of gradient walking energetics in man. *J Physiol*, 472:725-735.
89. Minetti AE, Ardigo LP, Saibene F (1994). Mechanical determinants of the minimum energy cost of gradient running in humans. *J Exp Biol*, 195:211-225.

-
90. Minetti AE, Capelli C, Zamparo P, di Prampero PE, Saibene F (1995). Effects of stride frequency on mechanical power and energy expenditure of walking. *Med Sci Sports Exerc*, 27:1194-1202.
 91. Minetti AE, Moia C, Roi GS, Susta D, Ferretti G (2002). Energy cost of walking and running at extreme uphill and downhill slopes. *J Appl Physiol*, 93:1039-1046.
 92. Myo T, Lammert O, Garby L (1985). Effect of trunk load on the energy expenditure of treadmill walking and ergometer cycling. *Eur J Appl Physiol Occup Physiol*, 54:122-124.
 93. Nakamura FY, Franchini E (2006). Maximal accumulated oxygen deficit as a predictor of anaerobic capacity. *Rev Bras Cineantropom Desempenho Hum*, 8:88-95.
 94. Nardello F, Ardigò LP, Minetti AE (2011). Measured and predicted mechanical internal work in human locomotion. *Human Mov Sci*, 30:90-104.
 95. Niven JE, Scharlemann JP (2005). Do insect metabolic rates at rest and during flight scale with body mass? *Biol Lett*, 1:346-349.
 96. Nummela A, Keranen T, Mikkelsen LO (2007). Factors related to top running speed and economy. *Int J Sports Med*, 28:655-661.
 97. Owles WH (1930). Alterations in the lactic acid content of the blood as a result of light exercise, and associated changes in the co(2)-combining power of the blood and in the alveolar co(2) pressure. *J Physiol*, 69:214-237.
 98. Peyré-Tartaruga LA. *The energetics and mechanics of human walking and running*. Porto Alegre, 2008. Doctoral Thesis. Federal University of do Rio Grande do Sul.
 99. Powers SK, Howley ET. (2012). *Exercise physiology: theory and applications to fitness and performance*. McGraw-Hill Education. Boston.
 100. Robertson RJ, Caspersen CJ, Allison TG, Skrinar GS, Abbott RA, Metz KF (1982). Differentiated perceptions of exertion and energy cost of young women while carrying loads. *Eur J Appl Physiol Occup Physiol*, 49:69-78.
 101. Rome LC, Sosnicki AA, Goble DO (1990). Maximum velocity of shortening of three fibre types from horse soleus muscle: implications for scaling with body size. *J Physiol*, 431:173-185.
 102. Rubner M (1883). Concerning the influence of body size on energy metabolism. *Z. Biol.*, 19:536-562.
 103. Saibene F, Minetti AE (2003). Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol*, 88:297-316.
 104. Saltin B, Astrand PO (1967). Maximal oxygen uptake in athletes. *J Appl Physiol*, 23:353-358.
 105. Saunders PU, Pyne DB, Telford RD, Hawley JA (2004). Factors affecting running economy in trained distance runners. *Sports Med*, 34:465-485.

106. Savage VM, Gilooly JF, Woodruff WH, West GB, Allen AP, Enquist BJ, Brown JH (2004). The predominance of quarter-power scaling in biology. *Funct Ecol*, 18:257-282.
107. Schepens B, Willems PA, Cavagna GA, Heglund NC (2001). Mechanical power and efficiency in running children. *Pflugers Arch*, 442:107-116.
108. Schmidt-Nielsen K (1975). Scaling in biology: the consequences of size. *J Exp Zool*, 194:287-307.
109. Scott CB, Roby FB, Lohman TG, Bunt JC (1991). The maximally accumulated oxygen deficit as an indicator of anaerobic capacity. *Med Sci Sports Exerc*, 23:618-624.
110. Sjodin B, Jacobs I (1981). Onset of blood lactate accumulation and marathon running performance. *Int J Sports Med*, 2:23-26.
111. Spencer MR, Gastin PB (2001). Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med Sci Sports Exerc*, 33:157-162.
112. Spriet LL (1992). Anaerobic metabolism in human skeletal muscle during short-term, intense activity. *Can J Physiol Pharmacol*, 70:157-165.
113. Suarez RK, Darveau CA, Childress JJ (2004). Metabolic scaling: a many-splendoured thing. *Comp Biochem Physiol B Biochem Mol Biol*, 139:531-541.
114. Symonds MR, Elgar MA (2002). Phylogeny affects estimation of metabolic scaling in mammals. *Evolution*, 56:2330-2333.
115. Tartaruga LAP, Coertjens M, Black GL, Tartaruga MP, Ribas LR, Krueel LFM (2003). Effects of fatigue on the kinematics of runners. *Braz J Biomech*, 4:39-44.
116. Tartaruga LAP, Tartaruga MP, Ribeiro JL, Coertjens M, Ribas LR, Krueel LFM (2004). Correlation between running economy and kinematic variables in high level runners. *Braz J Biomech*, 5:51-58.
117. Tartaruga MP, Beilke DD, Coertjens M, Baptista RR, Tartaruga LAP, Krueel LFM (2008). Relation between submaximum and maximum oxygen uptake of elite distance runners and elite rowers. *Rev Educ Física*, 141:22-33.
118. Tartaruga MP, Medeiros MHd, Alberton CL, Cadore EL, Peyré-Tartaruga LA, Baptista RR, Krueel LFM (2010). Application of the allometric scale for the submaximal oxygen uptake in runners and rowers. *Biol Sport.*, 27:297-300.
119. Tartaruga MP, Peyré-Tartaruga LA, Coertjens M, Medeiros MHd, Krueel LFM (2009a). The influence of the allometric scale on the relationship between running economy and biomechanical variables in distance runners. *Biol Sport.*, 26:263-273.
120. Tartaruga MP, Vaz FF, Coertjens M, Schmitt CD, Tiggemann CL, Krueel LFM (2009b). Comparison between protocols for determination of the anaerobic threshold in rowers. *Revista de Educação Física*, 145:21-27.

121. Taylor CR (1985). Force development during sustained locomotion: a determinant of gait, speed and metabolic power. *J Exp Biol*, 115:253-62.
122. Taylor CR, Heglund NC (1982). Energetics and mechanics of terrestrial locomotion. *Annu Rev Physiol*, 44:97-107.
123. Taylor CR, Heglund NC, Maloiy GM (1982). Energetics and mechanics of terrestrial locomotion. I. Metabolic energy consumption as a function of speed and body size in birds and mammals. *J Exp Biol*, 97:1-21.
124. Taylor CR, Heglund NC, McMahon TA, Looney TR (1980). Energetic cost of generating muscular force during running. *J Exp Biol*, 86:9-18.
125. Taylor CR, Longworth KE, Hoppeler H (1988). Matching O₂ delivery to O₂ demand in muscle: II. Allometric variation in energy demand. *Adv Exp Med Biol*, 227:171-181.
126. Taylor CR, Maloiy GM, Weibel ER, Langman VA, Kamau JM, Seeherman HJ, Heglund NC (1981). Design of the mammalian respiratory system. III Scaling maximum aerobic capacity to body mass: wild and domestic mammals. *Respir Physiol*, 44:25-37.
127. Taylor CR, Schmidt-Nielsen K, Raab JL (1970). Scaling of energetic cost of running to body size in mammals. *Am J Physiol*, 219:1104-1107.
128. Thomas S, Mooney PJ, Burrell MM, Fell DA (1997). Metabolic Control Analysis of glycolysis in tuber tissue of potato (*Solanum tuberosum*): explanation for the low control coefficient of phosphofructokinase over respiratory flux. *Biochem J*, 322:119-127.
129. Tieleman BI, Williams JB (2000). The adjustment of avian metabolic rates and water fluxes to desert environments. *Physiol Biochem Zool*, 73:461-479.
130. Turell DJ, Austin RC, Alexander JK (1964). Cardiorespiratory response of very obese subjects to treadmill exercise. *J Lab Clin Med*, 64:107-116.
131. Vaughan CL, O'Malley MJ (2005). Froude and the contribution of naval architecture to our understanding of bipedal locomotion. *Gait Posture*, 21:350-362.
132. Videler JJ, Weihs D (1982). Energetic advantages of burst-and-coast swimming of fish at high speeds. *J Exp Biol*, 97:169-178.
133. Wang Z, O'Connor TP, Heshka S, Heymsfield SB (2001). The reconstruction of Kleiber's law at the organ-tissue level. *J Nutr*, 131:2967-2970.
134. Wasserman K, McIlroy MB (1964). Detecting the threshold of anaerobic metabolism in cardiac patients during exercise. *Am J Cardiol*, 14:844-852.
135. Wasserman K, Whipp BJ, Koys SN, Beaver WL (1973). Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol*, 35:236-243.
136. Weibel ER, Bacigalupe LD, Schmitt B, Hoppeler H (2004). Allometric scaling of maximal metabolic rate in mammals: muscle aerobic capacity as determinant factor. *Respir Physiol Neurobiol*, 140:115-132.

137. Weibel ER, Hoppeler H (2005). Exercise-induced maximal metabolic rate scales with muscle aerobic capacity. *J Exp Biol*, 208:1635-1644.
138. Weibel ER, Taylor CR, Hoppeler H (1991). The concept of symmorphosis: a testable hypothesis of structure-function relationship. *Proc Natl Acad Sci U S A*, 88:10357-10361.
139. West GB, Brown JH, Enquist BJ (1997). A general model for the origin of allometric scaling laws in biology. *Science*, 276:122-126.
140. West GB, Brown JH, Enquist BJ (1999). The fourth dimension of life: fractal geometry and allometric scaling of organisms. *Science*, 284:1677-1679.
141. White CR, Seymour RS (2003). Mammalian basal metabolic rate is proportional to body mass^{2/3}. *Proc Natl Acad Sci U S A*, 100:4046-4049.
142. White CR, Seymour RS (2005). Allometric scaling of mammalian metabolism. *J Exp Biol*, 208:1611-1619.
143. Wickler SJ, Hoyt DF, Cogger EA, Hirschbein MH (2000). Preferred speed and cost of transport: the effect of incline. *J Exp Biol*, 203:2195-2200.
144. Willems PA, Cavagna GA, Heglund NC (1995). External, internal and total work in human locomotion. *J Exp Biol*, 198:379-393.
145. Williams KR, Cavanagh PR (1983). A model for the calculation of mechanical power during distance running. *J Biomech*, 16:115-128.
146. Williams KR, Cavanagh PR (1987). Relationship between distance running mechanics, running economy, and performance. *J Appl Physiol*, 63:1236-1245.

METODOLOGIA

A fim de atender o objetivo geral da presente tese, que foi analisar as relações da economia de corrida e da eficiência mecânica com o desempenho de corredores de rendimento usando modelos alométricos, foram realizados quatro estudos, um de revisão e três originais, a partir dos seguintes objetivos específicos:

3.1. OBJETIVO DO ESTUDO DE REVISÃO

Revisão bibliográfica sobre a predição do desempenho da corrida de meia e longa distância através da eficiência metabólica aplicando-se modelos alométricos.

3.2. OBJETIVO DO ESTUDO ORIGINAL 1

Identificar o efeito da escala alométrica na relação entre eficiência metabólica e desempenho em corrida de meia-distância de acordo com o nível de condicionamento físico.

3.3. OBJETIVO DO ESTUDO ORIGINAL 2

Investigar a relação entre trabalho mecânico e desempenho em corrida de longa distância em corredores recreacionistas aplicando-se a alometria.

3.4. OBJETIVO DO ESTUDO ORIGINAL 3

Examinar a influência do trabalho mecânico e do custo energético na eficiência mecânica da corrida.

3.5. HIPÓTESE GERAL DA TESE

Acredita-se que com a aplicação de expoentes alométricos específicos, as relações da economia de corrida e da eficiência mecânica com o desempenho de corredores de rendimento poderão se tornar mais precisas devido a utilização de valores de consumo de oxigênio mais representativos dos grupos investigados.

3.6. FINANCIAMENTO

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REVIEW

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

Efficiencia metabólica y predicción de la performance en carrera a pie de larga distancia: interés de la normalización alométrica

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4.1.1. SUMMARY

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. 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 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for oxygen consumption (VO_2) is inappropriate for comparing VO_2 values between subjects of different body characteristics. 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. Further studies are needed to investigate the ways in which REff can be used to predict running performance using allometric exponents.

4.1.2. 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 (VO_{2max}). 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, VO_{2max} and the ability to sustain a high percentage of VO_{2max} 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 $ml \cdot kg^{-1} \cdot min^{-1}$ is inappropriate for the purposes of comparing oxygen consumption between subjects of different body characteristics. In one of the first studies, Von Döbeln [33] found that VO_{2max} was related to fat-free body mass raised to the power of 0.71 in a mixed population (both sexes). More recently, Bergh, Sjödin, 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 $kg^{-2/3}$, as opposed to kg^{-1} . Furthermore, Sjödin and Svedenhag [34] suggested that changes in REff and VO_{2max} 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.

4.1.3. 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 $\frac{2}{3}$ 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].

$$Y = aX^b \quad (1)$$

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

$$\ln Y = \ln a + b \ln X \quad (2)$$

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-third 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) ($b = \frac{2}{3}$) 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 allometric exponent of two-third proposed by Rubner, based on body surface, was insufficient.

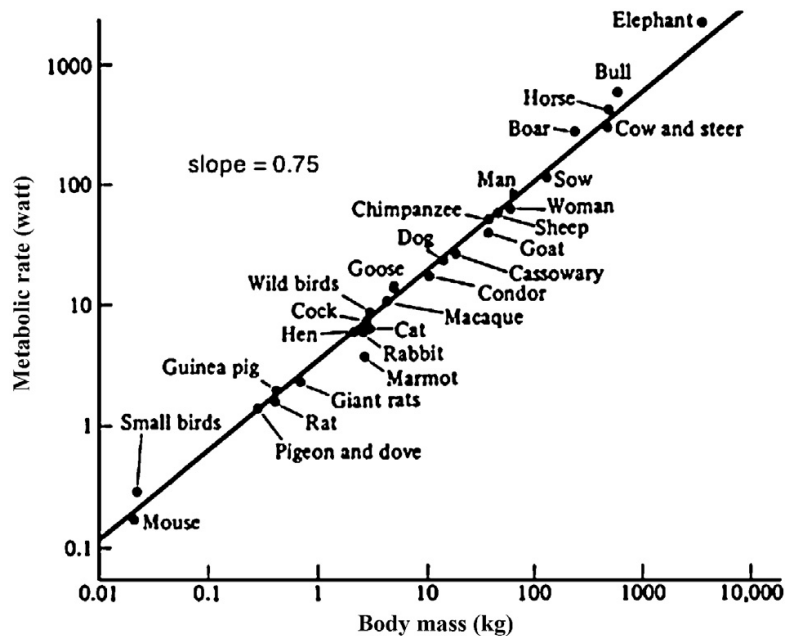


Figure 1 – Proportionality between metabolic rate and $\frac{3}{4}$ body mass [39].

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.

4.1.4. REFF 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].

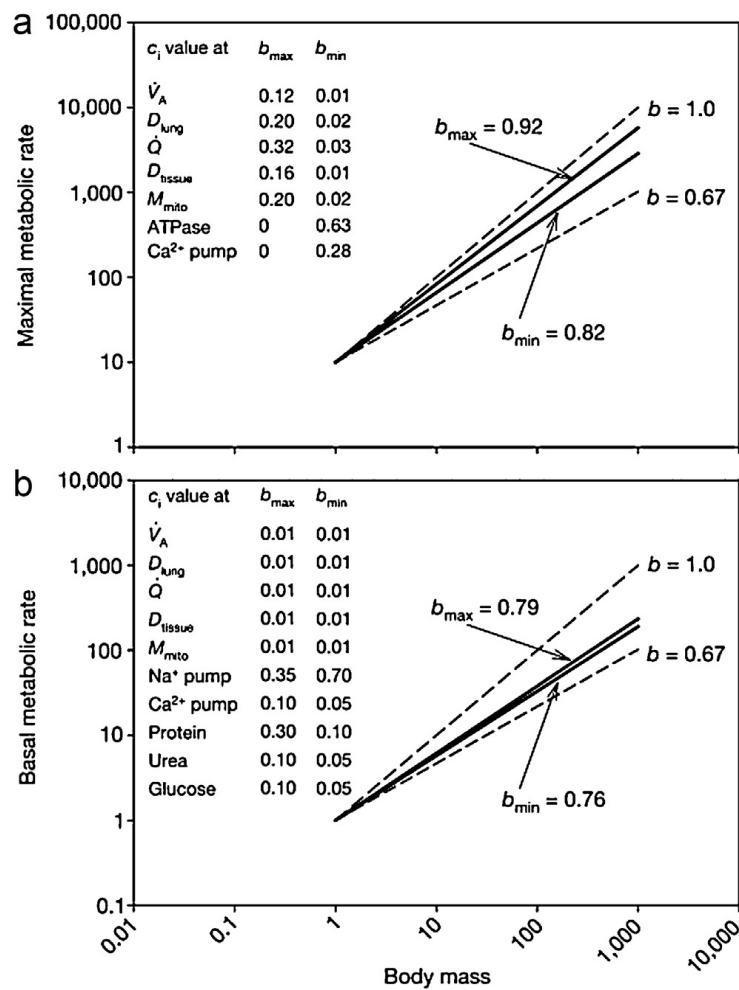


Figure 2 – For maximum metabolic rate (MMR) (a), the functions listed in order are control coefficient (c_i), alveolar ventilation (\dot{V}_A), pulmonary diffusion (D_{lung}), cardiac output (\dot{Q}), capillary-mitochondria tissue diffusion (D_{tissue}), cytosolic and mitochondrial metabolism (M_{mito}) plus actomyosin ATPase (ATPase) and the Ca²⁺ 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).

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 VO_{2max} ;
- a high fraction of VO_{2max} , which can be sustained throughout the competition;
- and a better REff [51].

Within this framework, even if high correlations have been identified between VO_{2max} and the running performance of groups of runners with different running abilities [52], in groups of

athletes of similar athletic capacities, VO_{2max} becomes a less sensitive predictor of performance, demonstrating the need to use other factors, such as the 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 VO_{2max} decreased by 10%. The fall of VO_{2max} was compensated by an improvement in REff and an increase of the lactate threshold from 80 to 88% VO_{2max} , thus suggesting an increase of the fraction of VO_{2max} sustainable throughout the effort, and demonstrating the important effect that REff can have on long-distance running performance.

The relationship between 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 REff throughout an event could explain the worst performance observed in some runners [9,54], although REff has been studied relatively less than other factors [3].

At a given running speed, the submaximal oxygen ($VO_{2submax}$) requirement (per $ml \cdot kg^{-1} \cdot min^{-1}$) may vary considerably between subjects [55]. For example a large variation in 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 REff of elite distance runners that are morphology similar and exhibit a relatively narrow range in VO_{2max} , 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 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 REff (Table 1). The studies by Coetzer 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 Cr (10%), (i.e., a better 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 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 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. $555 \text{ ml} \cdot \text{kg}^{-0.75} \cdot \text{km}^{-1}$) (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 Cr than those with relatively shorter lower limbs [64]. Future studies that quantify the effects the mass of the lower limbs and their distribution on total mechanical work has on REff and performance in

elite runners are suggested. 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.

Table 1 Reference values for aerobic cost of running in different populations.

Population	Maximal oxygen uptake	
	mL·kg ⁻¹ ·min ⁻¹	mL·kg ^{-0.75} ·min ⁻¹
Reference value (ACSM) (80 kg)	58	175
Elite Europeans/ North Americans (65 kg)	55	156
Elite East Africans (60 kg)	50	130

Foster and Lucia, 2007.
American College of Sports Medicine (ACSM).

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 morphology of different individuals [66,67] and/or subjects with different types of locomotion [12,68]. According to these studies, relative REff values should be used to generate comparisons between individuals of different body masses and surface (i. e., allometric exponents 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^{-3/4} and kg^{-2/3}, than to kg⁻¹. Furthermore, as was reported previously, Sjodin and Svedenhag [34] suggested that changes in REff and VO_{2max} (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_{2submax} and VO_{2max} 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 using proportional allometric models, Ingham et al. [14] demonstrated that a proportional curvilinear ratio of VO_{2max} 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_{2submax}, 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 $\dot{V}O_{2\max}$ (per $\text{L}\cdot\text{min}^{-1}$) and body mass (m) as predictor variables, the best predictor model of 5-km running performance was:

$$\text{Run speed (m}\cdot\text{s}^{-1}) = 84.3 (\dot{V}O_{2\max})^{1.01} (m)^{-1.03} \quad (3)$$

Table 2 Reference values for $\dot{V}O_{2\text{sub max}}$ in 15 rowers.

Submaximal oxygen uptake			
$\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$		$\text{mL}\cdot\text{kg}^{-0.68}\cdot\text{min}^{-1}$	
Rower 01	36.5	Rower 01	146.5
Rower 02	37.2	Rower 03*	147.4
Rower 03	37.6	Rower 04*	149.8
Rower 04	37.8	Rower 02*	150.7
Rower 05	38.5	Rower 05	152.8
Rower 06	39.1	Rower 07*	153.3
Rower 07	40.0	Rower 06*	154.4
Rower 08	40.4	Rower 08	157.3
Rower 09	41.0	Rower 10*	160.9
Rower 10	41.2	Rower 15*	162.6
Rower 11	42.1	Rower 14*	163.6
Rower 12	42.3	Rower 13*	163.7
Rower 13	42.6	Rower 12*	164.5
Rower 14	42.8	Rower 09*	170.3
Rower 15	42.9	Rower 11*	172.8

Tartaruga et al., 2010.

Submaximal oxygen uptake ($\dot{V}O_{2\text{sub max}}$). Changes in rower's performance prediction (*).

Table 3 Reference values for $\dot{V}O_{2\text{sub max}}$ in 11 runners.

Submaximal oxygen uptake			
$\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$		$\text{mL}\cdot\text{kg}^{-0.99}\cdot\text{min}^{-1}$	
Runner 01	41.0	Runner 01	42.7
Runner 02	41.5	Runner 02	43.2
Runner 03	43.0	Runner 03	44.8
Runner 04	44.2	Runner 04	46.0
Runner 05	44.6	Runner 05	46.3
Runner 06	45.5	Runner 06	47.4
Runner 07	46.1	Runner 07	48.1
Runner 08	46.5	Runner 08	48.3
Runner 09	46.8	Runner 09	48.8
Runner 10	47.3	Runner 10	49.4
Runner 11	51.2	Runner 11	53.4

Tartaruga et al., 2010.

Submaximal oxygen uptake ($\dot{V}O_{2\text{sub max}}$).

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 $\text{L}\cdot\text{min}^{-1}$) divided by body mass (in kg) or oxygen consumption (per $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) [47]. A similar result had been 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, $\text{VO}_{2\text{max}}$ (per $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).

Simply by adding or modifying variables in the allometric model, future research could explore whether the same scaling approach could be applied to, for example, alternative measures of recording power output to improve the prediction of time-trial performance [47].

4.1.5. 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

4.1.6. REFERENCES

- [1] Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc* 2000;32(1):70-84.
- [2] Di Prampero PE, Atchou G, Bruckner JC, Moia C. The energetics of endurance running. *Eur J Appl Physiol Occup Physiol* 1986;55(3):259-66.
- [3] Foster C, Lucia A. Running economy: the forgotten factor in elite performance. *Sports Med* 2007;37(4-5):316-9.
- [4] Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med* 2004;34(7):465-85.
- [5] Morgan DW, Craib M. Physiological aspects of running economy. *Med Sci Sports Exerc* 1992;24(4):456-61.
- [6] Bailey SP, Pate RR. Feasibility of improving running economy. *Sports Med* 1991;12(4):228-36.
- [7] Morgan DW, Martin PE, Krahenbuhl GS. Factors affecting running economy. *Sports Med* 1989;7(5):310-30.

- [8] Daniels JT. A physiologist's view of running economy. *Med Sci Sports Exerc* 1985;17(3):332-8.
- [9] Tartaruga MP, Brisswalter J, Peyre-Tartaruga LA, Avila AO, Alberton CL, Coertjens M, et al. The relationship between running economy and biomechanical variables in distance runners. *Res Q Exerc Sport* 2012;83(3):367-75.
- [10] Brisswalter J, Legros P, Durand M. Running economy, preferred step length correlated to body dimensions in elite middle distance runners. *J Sports Med Phys Fitness* 1996;36(1):7-15.
- [11] Tartaruga MP, Peyré-Tartaruga LA, Coertjens M, Medeiros MHD, Krueel LFM. The influence of the allometric scale on the relationship between running economy and biomechanical variables in distance runners. *Biol Sport* 2009;26(3):263-73.
- [12] Tartaruga MP, Medeiros MHD, Alberton CL, Cadore EL, Peyré-Tartaruga LA, Baptista RR, et al. Application of the allometric scale for the submaximal oxygen uptake in runners and rowers. *Biol Sport* 2010;27(4):297-300.
- [13] Bergh U, Sjodin B, Forsberg A, Svedenhag J. The relationship between body mass and oxygen uptake during running in humans. *Med Sci Sports Exerc* 1991;23(2): 205-11.
- [14] Ingham SA, Whyte GP, Pedlar C, Bailey DM, Dunman N, Nevill AM. Determinants of 800-m and 1500-m running performance using allometric models. *Med Sci Sports Exerc* 2008;40(2):345-50.
- [15] Nevill AM, Winter EM, Ingham S, Watts A, Metsios GS, Stewart AD. Adjusting athletes' body mass index to better reflect adiposity in epidemiological research. *J Sports Sci* 2010;28(9):1009-16.
- [16] Volianitis S, Secher NH. Rowing, the ultimate challenge to the human body - implications for physiological variables. *Clin Physiol Funct Imaging* 2009;29(4):241-4.
- [17] Bergh U. The influence of body mass in cross-country skiing. *Med Sci Sports Exerc* 1987;19(4):324-31.
- [18] West GB, Brown JH, Enquist BJ. A general model for the origin of allometric scaling laws in biology. *Science* 1997;276(5309):122-6.
- [19] Darveau CA, Suarez RK, Andrews RD, Hochachka PW. Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature* 2002;417(6885):166-70.
- [20] Nevill AM, Ramsbottom R, Williams C. Scaling physiological measurements for individuals of different body size. *Eur J Appl Physiol Occup Physiol* 1992;65(2):110-7.
- [21] Nevill AM, Allen SV, Ingham SA. Modelling the determinants of 2000 m rowing ergometer performance: a proportional, curvilinear allometric approach. *Scand J Med Sci Sports* 2011;21(1):73-8.
- [22] Nevill A, Rowland T, Goff D, Martel L, Ferrone L. Scaling or normalising maximum oxygen uptake to predict 1-mile run time in boys. *Eur J Appl Physiol* 2004;92(3):285-8.

- [23] Rubner M. Über den einfluss der körpergrösse auf stoff und kraftwechsel. *Z Biol* 1883;19:536-62.
- [24] Chirinos JA, Segers P, De Buyzere ML, Kronmal RA, Raja MW, De Bacquer D, et al. Left ventricular mass: allometric scaling, normative values, effect of obesity, and prognostic performance. *Hypertension* 2010;56(1):91-8.
- [25] Vanderburgh PM, Katch FI, Schoenleber J, Balabinis CP, Elliott R. Multivariate allometric scaling of men's world indoor rowing championship performance. *Med Sci Sports Exerc* 1996;28(5):626-30.
- [26] Heil DP. Scaling of submaximal oxygen uptake with body mass and combined mass during uphill treadmill bicycling. *J Appl Physiol* 1998;85(4):1376-83.
- [27] Loftin M, Sothorn M, Trosclair L, O'Hanlon A, Miller J, Udall J. Scaling VO₂ peak in obese and non-obese girls. *Obes Res* 2001;9(5):290-6.
- [28] Jensen K, Johansen L, Secher NH. Influence of body mass on maximal oxygen uptake: effect of sample size. *Eur J Appl Physiol* 2001;84(3):201-5.
- [29] Goosey-Tolfrey VL, Batterham AM, Tolfrey K. Scaling behavior of VO₂ peak in trained wheelchair athletes. *Med Sci Sports Exerc* 2003;35(12):2106-11.
- [30] Chamari K, Moussa-Chamari I, Boussaidi L, Hachana Y, Kaouech F, Wisloff U. Appropriate interpretation of aerobic capacity: allometric scaling in adult and young soccer players. *Br J Sports Med* 2005;39(2):97-101.
- [31] Jobson SA, Woodside J, Passfield L, Nevill AM. Allometric scaling of uphill cycling performance. *Int J Sports Med* 2008;29(9):753-7.
- [32] Lamberts RP, Lambert MI, Swart J, Noakes TD. Allometric scaling of peak power output accurately predicts time trial performance and maximal oxygen consumption in trained cyclists. *Br J Sports Med* 2012;46(1):36-41.
- [33] Von Döbeln W. Maximal oxygen intake, body size, and total hemoglobin in normal man. *Acta Physiol Scand* 1956;38(2):193-9.
- [34] Sjodin B, Svedenhag J. Oxygen uptake during running as related to body mass in circumpubertal boys: a longitudinal study. *Eur J Appl Physiol Occup Physiol* 1992;65(2):150-7.
- [35] Jones JH, Lindstedt SL. Limits to maximal performance. *Annu Rev Physiol* 1993;55:547-69.
- [36] Suarez RK, Darveau CA, Childress JJ. Metabolic scaling: a many splendoured thing. *Comp Biochem Physiol B Biochem Mol Biol* 2004;139(3):531-41.
- [37] Kleiber M. Body size and metabolism. *Hilgardia* 1932;6:315-53.
- [38] Taylor CR, Schmidt-Nielsen K, Raab JL. Scaling of energetic cost of running to body size in mammals. *Am J Physiol* 1970;219(4):1104-7.
- [39] Kleiber M. Body size and metabolic rate. *Physiol Rev* 1947;27(4):511-41.

- [40] Dodds PS, Rothman DH, Weitz JS. Re-examination of the “3/4- law” of metabolism. *J Theor Biol* 2001;209(1):9-27.
- [41] White CR, Seymour RS. Mammalian basal metabolic rate is proportional to body mass $2/3$. *Proc Natl Acad Sci U S A* 2003;100(7):4046-9.
- [42] Nevill AM. The need to scale for differences in body size and mass: an explanation of Kleiber’s 0.75 mass exponent. *J Appl Physiol* 1994;77(6):2870-3.
- [43] Weibel ER, Bacigalupe LD, Schmitt B, Hoppeler H. Allometric scaling of maximal metabolic rate in mammals: muscle aerobic capacity as determinant factor. *Respir Physiol Neurobiol* 2004;140(2):115-32.
- [44] Barbosa LA, Castro e Silva A, da Silva JK. Scaling relations in food webs. *Phys Rev E Stat Nonlin Soft Matter Phys* 2006;73(4 Pt 1):041903.
- [45] Banavar JR, Maritan A, Rinaldo A. Size and form in efficient transportation networks. *Nature* 1999;399(6732):130-2.
- [46] Hochachka PW, Darveau CA, Andrews RD, Suarez RK. Allometric cascade: a model for resolving body mass effects on metabolism. *Comp Biochem Physiol A Mol Integr Physiol* 2003;134(4):675-91.
- [47] Nevill AM, Jobson SA, Palmer GS, Olds TS. Scaling maximal oxygen uptake to predict cycling time-trial performance in the field: a non-linear approach. *Eur J Appl Physiol* 2005;94(5-6):705-10.
- [48] Heglund NC, Fedak MA, Taylor CR, Cavagna GA. Energetics and mechanics of terrestrial locomotion. IV. Total mechanical energy changes as a function of speed and body size in birds and mammals. *J Exp Biol* 1982;97:57-66.
- [49] Taylor CR, Heglund NC, Maloiy GM. Energetics and mechanics of terrestrial locomotion. I. Metabolic energy consumption as a function of speed and body size in birds and mammals. *J. Exp Biol* 1982;97:1-21.
- [50] Hauswirth C, Brisswalter J. Strategies for improving performance in long duration events: Olympic distance triathlon. *Sports Med* 2008;38(11):881-91.
- [51] Lazzer S, Salvadego D, Rejc E, Buglione A, Antonutto G, di Prampero PE. The energetics of ultra-endurance running. *Eur J Appl Physiol* 2012;112(5):1709-15.
- [52] Sjodin B, Svedenhag J. Applied physiology of marathon running. *Sports Med* 1985;2(2):83-99.
- [53] Jones AM. A five year physiological case study of an Olympic runner. *Br J Sports Med* 1998;32(1):39-43.
- [54] Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc* 1980;12(5):357-60.

- [55] Svedenhag J. Maximal and submaximal oxygen uptake during running: how should body mass be accounted for? *Scand J Med Sci Sports* 1995;5(4):175-80.
- [56] Svedenhag J, Sjodin B. Maximal and submaximal oxygen uptakes and blood lactate levels in elite male middle- and long-distance runners. *Int J Sports Med* 1984;5(5):255-61.
- [57] Lucia A, Esteve-Lanao J, Olivan J, Gomez-Gallego F, San Juan AF, Santiago C, et al. Physiological characteristics of the best Eritrean runners-exceptional running economy. *Appl Physiol Nutr Metab* 2006;31(5):530-40.
- [58] Saltin B, Larsen H, Terrados N, Bangsbo J, Bak T, Kim CK, et al. Aerobic exercise capacity at sea level and at altitude in Kenyan boys, junior and senior runners compared with Scandinavian runners. *Scand J Med Sci Sports* 1995;5(4): 209-21.
- [59] Coetzer P, Noakes TD, Sanders B, Lambert MI, Bosch AN, Wiggins T, et al. Superior fatigue resistance of elite black South African distance runners. *J Appl Physiol* 1993;75(4):1822-7.
- [60] Larsen HB. Kenyan dominance in distance running. *Comp Biochem Physiol A Mol Integr Physiol* 2003;136:161-70.
- [61] Bosch AN, Goslin BR, Noakes TD, Dennis SC. Physiological differences between black and white runners during a treadmill marathon. *Eur J Appl Physiol* 1990;61:68-72.
- [62] Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. *J Physiol* 1977;268(2):467-81.
- [63] Willems PA, Cavagna GA, Heglund NC. External, internal and total work in human locomotion. *J Exp Biol* 1995;198(Pt 2):379-93.
- [64] Steudel-Numbers KL, Weaver TD, Wall-Scheffler CM. The evolution of human running: effects of changes in lowerlimb length on locomotor economy. *J Hum Evol* 2007;53(2): 191-6.
- [65] Ferretti G, Atchou G, Grassi B, Marconi C, Cerretelli P. Energetics of locomotion in African pygmies. *Eur J Appl Physiol Occup Physiol* 1991;62(1):7-10.
- [66] Svedenhag J, Sjodin B. Body-mass-modified running economy and step length in elite male middle- and long-distance runners. *Int J Sports Med* 1994;15(6):305-10.
- [67] Vanderburgh PM, Dooman C. Considering body mass differences, who are the world's strongest women? *Med Sci Sports Exerc* 2000;32(1):197-201.
- [68] Saltin B, Astrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol* 1967;23(3):353-8.
- [69] Glazier DS. Beyond the 3/4-power law: variation in the intra and interspecific scaling of metabolic rate in animals. *Biol Rev* 2005;80(1):611-62.
- [70] Winter EM, Hamley EJ. Sub maximal oxygen uptake related to fat free mass and lean leg volume in trained runners. *Br J Sports Med* 1976;10(4):223-5.

International Journal of Sports Physiology and Performance**SCALE MODEL ON PERFORMANCE PREDICTION IN RECREATIONAL AND ELITE ENDURANCE RUNNERS**

(Original article)

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4.2.1. SUMMARY

Identify the effect of allometric scaling on the relationship between running efficiency (*REff*) and middle-distance running performance according to performance level. Thirteen recreational middle-distance runners (male, mean \pm SD - age: 33 ± 8 years; body mass: 76.4 ± 8.6 kg; maximal oxygen uptake - VO_{2max} : 52.8 ± 4.6 ml \cdot kg $^{-1}\cdot$ min $^{-1}$) (G1) and thirteen high-level middle-distance runners (male, age: 25 ± 4 years; body mass: 62.8 ± 2.7 kg; VO_{2max} : 70.4 ± 1.9 ml \cdot kg $^{-1}\cdot$ min $^{-1}$) (G2) performed a continuous incremental test to volitional exhaustion in order to determine VO_{2max} and a running submaximal test of 6-min at 70% of VO_{2max} to assess *REff*. Significant correlations between *REff* and performance were found for both groups. However, the best correlation was observed in recreational runners when using the allometric exponent (respectively for G1; non allometric vs. allometric scaling: $r = 0.80$ vs. $r = 0.86$; and for G2; non allometric vs. allometric scaling: $r = 0.55$ vs. $r = 0.50$). These results indicate that an allometric normalization may improve endurance performance prediction from *REff* values in recreational, but not in elite, runners.

4.2.2. INTRODUCTION

Classically, maximal oxygen uptake (VO_{2max}), running efficiency (*REff*) and anaerobic threshold are the main parameters that have been used to predict performance during middle- and long-distance running events.^{1,2}

REff could be defined either from the steady-state submaximal oxygen uptake at given velocities (running economy - *RE*)³ or from energy expenditure per-unit distance (energy cost of running - *Cr*).⁴ According to previous reports by Daniels,⁵ *REff* can vary among runners that have a similar VO_{2max} by as much as 30% or more. However, despite the fact that the role of *REff* on running performance has been reported since the 1970s, *REff* has been recently described as “the forgotten factor in elite performance” since little scientific literature has

been produced in this area compared with other intervening variables of performance (i.e. VO_{2max} and the ability to sustain a high percentage of VO_{2max}).⁶

Among factors affecting the relationship between *REff* and middle-or long-distance running performance, some authors have investigated the way by which the morphological aspects (i.e. body size and body surface) affect performance.⁷⁻¹¹ This effect could be observed for example in Kenyan and Ethiopian runners that often dominate middle- and long-distance events in athletics. In these subjects running is systematically more economical because they generally have a smaller body size and a thinner lower leg than other runners.⁶ Within this framework, some researchers have suggested the use of allometric scaling for efficiency assessment in order to consider the effect of anthropometric characteristics on metabolic measures and particularly on *REff*.⁷⁻¹¹ These authors demonstrated that an indiscriminate use of the unit $ml\text{kg}^{-1}\text{min}^{-1}$ is inappropriate to compare oxygen consumption between subjects with different body characteristics.^{12,13} In one of the first studies, Bergh et al¹⁰ indicated that oxygen consumption during running does not increase linearly to body mass and, as such, they proposed that in maximal or submaximal intensity, oxygen consumption needs to be relativized to $\text{kg}^{-0.75}$ and $\text{kg}^{-0.66}$, and not to kg^{-1} . However, these theoretical exponents have been questioned in athletes, children and individuals with different levels of performance and body composition.^{14,15} It becomes necessary to derivate the allometric exponent for each variable. Batterham¹⁵ tested the relationship between body size and metabolic rate from submaximal to maximal aerobic conditions in 1629 healthy men, and found that the mass scaling exponent ranged from $\text{kg}^{-0.83}$ to $\text{kg}^{-0.94}$, suggesting that is necessary to calculate an exponent specific for *REff*.

Another possible confusing factor in the use of allometric scaling to assess oxygen consumption could be due to differences in aerobic capacity among subjects (i.e. untrained or moderately trained vs. runners that compete at a high level).¹⁴ In a recent study analyzing the allometric relationship between oxygen consumption (ranging from rest to maximal condition) and body mass in trained and untrained individuals Markovic, Vucetic and Nevill¹⁴ found that the allometric model may be valid in describing the scaling behaviour of metabolic rate in untrained individuals but not in athletes. This last result suggests that the interest to use an allometric scaling to predict performance from *REff* values could depend on aerobic capacity or performance level. To the best of our knowledge, few studies has examined the effect of performance level on the usefulness to use an allometric model to predict endurance running performance from *REff* values.

Thus, the purpose of this study was to examine the effect of allometric scaling on the relationship between *REff* and endurance running performance according to performance level. In comparison to elite endurance runners, our hypothesis was that the allometric model might better predicting the endurance performance in recreational endurance runners.

4.2.3. METHODS

4.2.3.1. SUBJECTS

Thirteen recreational middle-distance runners (male, mean age \pm SD: 33 \pm 8 years) (G1) and thirteen high-level middle-distance runners competing at international level (male, age: 25 \pm 4 years) (G2) participated in this study. Subjects were free of any musculoskeletal, bone and joint, or cardiac and pulmonary diseases and were not taking any medications. Calculation of the sample “*n*” was carried out using the PEPI program (Version 4.0) with a power of 90%. In order to participate in this study, all subjects were required to read and sign the written informed consent form, which contained all the information about the procedures and potential risks associated with participating in the study. The study was approved by the local University’s Institutional Ethics and Research Committee and is in accordance with the Declaration of Helsinki.

4.2.3.2. EXPERIMENTAL PROCEDURES

Each subject took part in three experimental laboratory sessions (sample characterization, incremental treadmill (QUINTON, Waukesha, USA) running protocol and *REff* determination test) (see Fig. 1). An interval of 48 h was used between the sessions. The laboratory ambient temperature (25°C) and relative humidity (53%) were controlled according to ISO-8573-1 (International Standards). Several restrictions were imposed on the subjects: no food 3-4 h before the tests and any stimulants or intense physical activity 12 h before each evaluation.

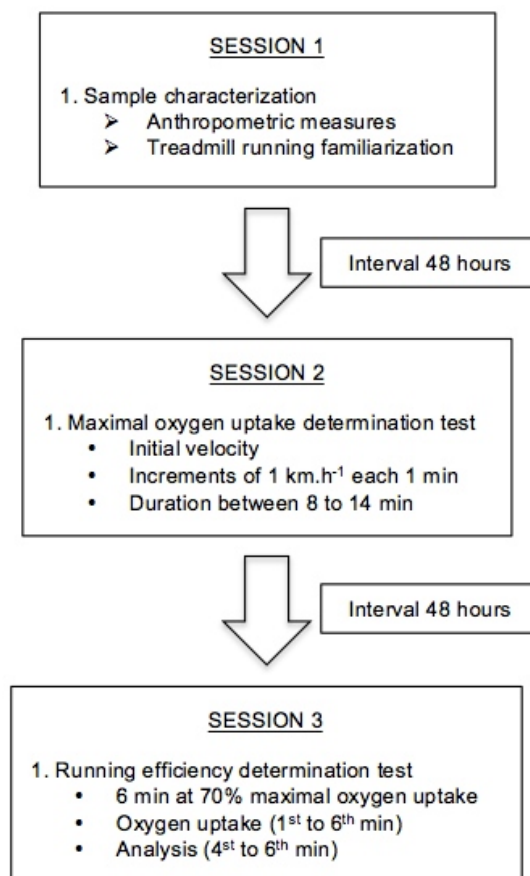


Figure 1. Experimental laboratory sessions.

4.2.3.3. SAMPLE CHARACTERIZATION

Body mass was assessed to the nearest 0.1 kg using a beam balance scale with the runners wearing minimal clothing. During the sample characterization session, all subjects participated in a familiarization exercise on treadmill running with initial velocity of $10 \text{ km}\cdot\text{h}^{-1}$ and increases by $1 \text{ km}\cdot\text{h}^{-1}$ at 1-min intervals until volitional exhaustion, with specific ergospirometric accessories. In addition, all details of the care that would need to be taken while performing the exercise were explained.

4.2.3.4. INCREMENTAL TREADMILL RUNNING PROTOCOL

After a brief warm-up and 10-min rest, subjects performed a progressive protocol with an initial velocity of $10 \text{ km}\cdot\text{h}^{-1}$ and increased by $1 \text{ km}\cdot\text{h}^{-1}$ at 1-min intervals. The treadmill incline was fixed at 1%. Load increments were calculated to reach $\text{VO}_{2\text{max}}$ between 8 and 14 min. The $\text{VO}_{2\text{max}}$ attainment criteria described by Howley, Bassett and Welch¹⁶ (i.e. maintenance in $\text{VO}_{2\text{max}}$ with increase in the exercise intensity; a respiratory exchange ratio greater than 1.15 was reached; estimated maximal HR was reached) were adopted. When the peak $\text{VO}_{2\text{max}}$ was considered as $\text{VO}_{2\text{max}}$. Respiratory parameters were continuously recorded using a metabolic cart (MGC/CPX; St. Paul, USA) with gas exchange and ventilatory analyzed breath by breath, previously calibrated according to manufacturer's specifications.

4.3.3.5. REFF DETERMINATION TEST

The *REff* test was a 6-min run at 70% of $\text{VO}_{2\text{max}}$. This intensity was chosen to correspond to a predominantly aerobic exercise for all subjects ($13 \pm 4.9\%$ of anaerobic threshold) and thus to allow the assessment of efficiency from oxygen consumption values.⁵ Individual *REff* values (cost of transport in $\text{J}\cdot\text{kg}^{-1}\cdot\text{m}$, with respiratory quotient corrected by 20.1) were determined based on the mean submaximal oxygen uptake values recorded during the last two minutes of the test. The breath-by-breath data were smoothed with a 15-s moving average. In this study, *REff* was considered as the energy expenditure per-unit distance (energy cost of running - *Cr*).

4.2.3.6. PERFORMANCE

Performance was assessed from the best performance (fastest times) in middle distance events ranging from 3000-m steeplechase run (G2) to 10000-m run (G1) performed at the latest in the month following laboratory testing. In order to compare different middle distance events, performance was scored in points according to the International Association of Athletic Federations (IAAF) table (Hungarian table).

4.2.3.7. ALLOMETRIC SCALING

To understand the relationship between $REff$ and running performance it was used allometric normalization that can be described by the general equation:

$$y = ax^b \quad (1)$$

where y is absolute VO_{2max} , x is body mass, b is the allometric or scaling exponent, and a is a constant characteristic for the organism, which is called the allometric coefficient.^{8,12,17} For determination of b , the exponential function was transformed into a linear function:

$$\log y = b \cdot \log \text{mass} + \log a \quad (2)$$

where b is the slope of the linear regression line on a double logarithmic plot.¹⁸

4.2.3.8. STATISTICAL ANALYSIS

The Shapiro-Wilk test was used to verify the normality of the data. The Pearson product-moment correlation test and multiple linear regression analysis were used to analyze the relationship between $REff$ and endurance running performance (in times). Possible differences between groups were analyzed using two samples t-test with unequal variances and one-way ANOVA with Bonferroni post-hoc test. Significance was accepted as $p \leq 0.05$, statistical power was 90%, and analyses were performed in SPSS Version 20.0.

4.2.4. RESULTS

Performance values scored according to the IAAF Hungarian table and physiological characteristics are shown in Table 1. As expected, high-level runners had significantly higher ($p < 0.05$) performance scores than recreational runners. Significant differences were observed in age ($p = 0.006$) and body mass ($p = 0.001$). No significant differences were found in HR_{max} between groups ($p = 0.379$). The performance (in times; min:s) for G1 and G2 was 43:40 \pm 2:27 and 8:29 \pm 0:8, respectively.

Table 1. Performance score according to the IAAF Hungarian table and physiological characteristics of subjects Mean \pm SD.

	G1 (10000-m)	G2 (3000-m)
Performance (pts.)	166.8 \pm 84.56	1139.9* \pm 35.25
Body mass (kg)	76.4 \pm 8.6	62.8* \pm 2.7
Heart rate $_{max}$ (bpm)	187 \pm 12	190 \pm 10

Note: Recreational (G1) and high-level (G2) middle-distance runners.

* When a difference was found between groups, $p < 0.05$.

The relationship between VO_{2max} and body mass for recreational (G1) and high-level runners (G2) (see Fig. 2) was conformed to the allometric expression, with similar allometric exponents ($r = 0.72$, $p = 0.005$ and 0.79 , $p = 0.001$, respectively). These common exponents

were capable to adjust the effects of body size on $REff$. Significant differences in VO_{2max} values with and without the application of specific allometric exponents were observed between groups and significant correlations between VO_{2max} and performance, with and without the application of specific allometric exponents, were observed only in recreational runners (G1) and in the general group (Gtotal) but not in the high level group (G2) (Table 2).

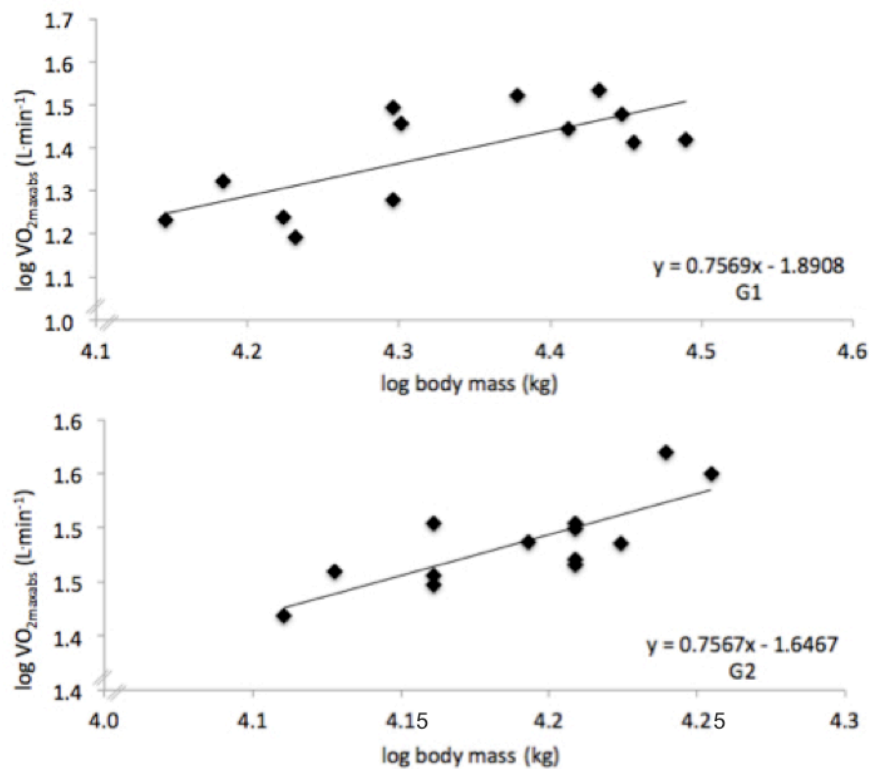


Figure 2. Relationships between maximal oxygen uptake expressed in absolute terms ($VO_{2maxabs}$) and body mass by using allometric log-linear for recreational (G1; $n = 13$) and high-level middle-distance runners (G2; $n = 13$). Regression lines are shown with the 95% confidence interval.

Table 2. Relationships between VO_{2max} and performance for recreational (G1), high-level (G2) middle-distance runners and general group (Gtotal) with and without the use of allometric exponent.

	G1 ($n = 13$)			G2 ($n = 13$)			Gtotal ($n = 26$)		
	Mean	SD	r	Mean	SD	r	Mean	SD	r
$VO_{2maxabs}$	3985.1	± 435.0	-0.16	4423.0 ^a	± 183.4	-0.03	4204.1	± 396.0	-0.57*
VO_{2max} ($b = 1$)	52.8	± 4.6	-0.94*	70.4 ^a	± 1.9	-0.07	61.2 ^b	± 10.0	-0.93*
VO_{2max} ($b = 0.75$)	152.0	± 12.5	-0.88*	194.0 ^a	± 4.9	-0.07	172.5 ^b	± 25.4	-0.92*

Note: (b) allometric exponent; maximal oxygen uptake expressed in $ml \cdot min^{-1}$ and $ml \cdot kg^{-b} \cdot min^{-1}$.

^a Significant difference in comparison with G1;

^b Significant difference in comparison with G2 and G2;

* $p < 0.05$.

The average speeds during the $REff$ determination test were respectively for G1 and G2: 13 $km \cdot h^{-1}$ vs. 15 $km \cdot h^{-1}$. The relationships between $REff$ and performance for recreational and high-level middle-distance runners, with and without the use of allometric exponent, are shown in Table 3, with the confidence limits presented in Table 4. The inter-group variability

(G1-G2; G1-Gtotal; G2-Gtotal) in *REff* values, with and without the application of specific allometric exponents, was: 12.3 % and 17.5 %; 6.7 % and 8,9 %; 5.3 % and 7.9 %.

Table 3. Relationships between *REff* and performance for recreational (G1), high-level (G2) middle-distance runners and general group (Gtotal) with and without the use of allometric exponent.

Situation	G1 (n = 13) 13 km·h ⁻¹			G2 (n = 13) 15 km·h ⁻¹			Gtotal (n = 26)		
	Mean	SD	r	Mean	SD	r	Mean	SD	r
Cr (J·m ⁻¹)	260.1	± 42.4	0.75*	248.7	± 22.7	0.44	254.4	± 33.8	0.23
Cr (J·kg ⁻¹ ·m ⁻¹)	3.37	± 0.15	0.80*	3.96	± 0.32	0.55*	3.67	± 0.39	-0.75*
Cr (J·kg ^{-0.75} ·m ⁻¹)	9.71	± 0.63	0.86*	10.91	± 0.91	0.50*	10.36	± 1.05	-0.58*

Note: (b) allometric exponent. *REff* values expressed in cost of running (Cr).
p < 0.05.

Table 4. Confidence limits of the correlations coefficients of *REff* for recreational (G1), high-level (G2) middle-distance runners and general group (Gtotal) with and without the use of allometric exponent.

Situation	G1 (n = 13)		G2 (n = 13)		G3 (n = 13)	
	Lower	Upper	Lower	Upper	Lower	Upper
Cr (J·kg ⁻¹ ·m ⁻¹)	3.29	3.45	3.79	4.13	3.46	3.88
Cr (J·kg ^{-0.75} ·m ⁻¹)	9.37	10.05	10.42	11.40	9.79	10.93

Note: (b) allometric exponent. *REff* values expressed in cost of running (Cr).
Significant difference intragroup.

Significant correlations were found between *REff* and performance for both groups indicating that *REff* can be considered as an important factor of middle distance performance whatever the performance level. However, the strongest correlations values were observed in the recreational runners, especially when using the allometric exponent. When using multiple regression analysis, the overall prediction power model of independent variables (body mass, VO_{2max} with kg⁻¹ and *REff*) was 91.0%, with an estimation error of 3.23.

4.2.5. DISCUSSION

In the present study we examined the effect of allometric scaling on the relationship between *REff* and middle distance running performance according to performance level.

Firstly, one interesting result of this study is that the applications of linear models allowed the determination of a similar allometric exponent for both groups (see Fig. 2). The relationship between body mass and metabolic rate has been investigated in animals and humans by biologists and healthcare professionals throughout the world from the beginning of the 19th century until today.^{9,11,17} Our exponents are in agreement with the findings by Kleiber,¹⁹ who studied the relationship between metabolic rate and body mass in rats and birds of different sizes, indicating the interest to use an allometric exponent to ¾ of body mass to express metabolic rate (r = 0.98). More recently, a similar exponent was also verified by Bergh et al,¹⁰ who indicated that oxygen consumption during running does not increase proportionally to body mass and this physiological variable needs to be relativized to kg^{-0.75}. In general, studies have shown that the allometric exponent is morphologically specific according

to the group investigated, especially the behavior of $\dot{V}O_{2\max}$, body mass^{9,20,21} and body geometry.^{22,23} This hypothesis could therefore explain a similar allometric exponent between our groups despite difference in body size or performance level in animals and humans.

The most important finding of this study indicate statistically significant correlations between *REff* and performance whatever the groups, demonstrating that *REff* could be a significant factor to predict middle-distance running performance. This result is in agreement with previous studies indicating the role of *REff* in endurance performance and the interest to improve this parameter with training.^{6,24-26} However, in this study, comparing groups with different performance level, the strongest correlations were observed in the recreational runners, especially when using the allometric exponent, demonstrating the interest of allometric scaling to express efficiency or oxygen consumption in such population (see Table 3). Moreover, even if a significant, but lower, correlation was found for high-level runners, inconsiderable effect of allometric scaling was observed.

This result could be discussed with those reported by Markovic, Vucetic and Nevill,¹⁴ comparing the allometric relationship between human metabolic rate (ranging from resting to maximal metabolic conditions) and body mass, both in athletes of different specialization and untrained individuals. In this study, for untrained individuals, the allometric exponent value exhibited an increase when increasing metabolic demand ($b = 0.69, 0.76, 0.76, 0.84$ and 0.89 , respectively). In contrast, the allometric exponent value for the athletic group significantly decreased when moving from resting to maximal metabolic conditions ($b = 0.98, 0.88, 0.80, 0.69$, and 0.67). This last result indicate that the allometric cascade model proposed by Darveau et al¹² may be valid in describing the scaling behavior of metabolic rate in untrained individuals, but not in athletes of different specializations. This different usefulness of allometric scaling among subjects with different aerobic capacities is also reported in our study when we analyze de relationship between *REff* and performance. In our study, despite the fact that, we found a similar allometric exponent for recreational and high-level runners, corroborating with Kleiber,^{19,27} we also observed that the use of allometric scaling may be more effective in predicting the performance in untrained individuals in comparison to athletes, and this results can be also related to heterogeneity in body composition among subjects¹⁵.

Furthermore, another interesting but more classical result of this comparison between groups of different performance level is that a significant relationship between $\dot{V}O_{2\max}$ and performance, was only observed for recreational middle-distance runners. This observation is in agreement for example with previous studies indicating that in a homogeneous group of well trained runners small variations in $\dot{V}O_{2\max}$ values are observed in athletes with similar performance, demonstrating that this variable is not a good predictor of the performance in high-level subjects.^{2,28}

These observations raise the difficulty to identify factors of performance in high-level athletes. On the one hand, classical assessment of oxygen uptake using efficiency or $\dot{V}O_{2\max}$ may represent only one dimension of the aerobic capability response. For example, the time constant of “switch-on” and the time spent at a high proportion of $\dot{V}O_{2\max}$ may also be important factors that explain the potential for aerobic energy turnover.¹¹ On the other hand,

in high level athletes with a high running velocities and different pacing strategies during competition, neuromuscular factors and anaerobic contribution need to be take in account in performance prediction.²⁹

4.2.6. PRACTICAL APPLICATION

Differences in body mass account for almost 70% of the differences observed in VO_{2MAX} and $REff$ test in recreational runners. Generally measured on per unit mass basis, it reduces the obvious disparities that will be observed in runners of differing total body mass. However, while expressing VO_{2max} or $REff$ on a per unit weight basis will control for differences in total body mass, it does not eliminate the differences in body composition, demonstrating that an indiscriminate use of kg^{-1} is inappropriate to compare subjects with different body characteristics. The findings of the current study demonstrate that the allometric model is a good method to determine and comparing the endurance performance prediction in recreational endurance runners; an alternative simple and interesting that can improve the effectiveness on physical aerobic training.

4.2.7. CONCLUSION

Previous research indicated that $REff$ is a factor of endurance running performance. Moreover, it has been demonstrated that oxygen consumption does not increase linearly to body mass during running activities.^{6,7,10,30} As such, relativizing the oxygen uptake by total body mass may produce erroneous interpretations when compared the $REff$ of groups comprising morphologically different runners. In weight-supported events, studies have demonstrated that allometric scaling can improve the relationship between $REff$ and performance. Our study showed that this improvement mainly occur in recreational middle-distance runners in comparison to elite middle-distance runners, probably due to physiological aspects as aerobic capacity or performance level.

4.2.8. REFERENCES

1. Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Med.* 2007;37:857-880.
2. Sjodin B, Svedenhag J. Applied physiology of marathon running. *Sports Med.* 1985;2:83-99.
3. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc.* 2000;32:70-84.
4. Di Prampero PE, Atchou G, Bruckner JC, Moia C. The energetics of endurance running. *Eur J Appl Physiol Occup Physiol.* 1986;55:259-266.

5. Daniels JT. A physiologist's view of running economy. *Med Sci Sports Exerc.* 1985;17:332-338.
6. Foster C, Lucia A. Running economy: the forgotten factor in elite performance. *Sports Med.* 2007;37:316-319.
7. Brisswalter J, Legros P, Durand M. Running economy, preferred step length correlated to body dimensions in elite middle distance runners. *J Sports Med Phys Fitness.* 1996;36:7-15.
8. Tartaruga MP, Peyré-Tartaruga LA, Coertjens M, Medeiros MHd, Kruel LFM. The influence of the allometric scale on the relationship between running economy and biomechanical variables in distance runners. *Biol Sport.* 2009;26:263-273.
9. Tartaruga MP, Medeiros MHd, Alberton CL, Cadore EL, Peyré-Tartaruga LA, Baptista RR, Kruel LFM. Application of the allometric scale for the submaximal oxygen uptake in runners and rowers. *Biol Sport.* 2010;27:297-300.
10. Bergh U, Sjodin B, Forsberg A, Svedenhag J. The relationship between body mass and oxygen uptake during running in humans. *Med Sci Sports Exerc.* 1991;23:205-211.
11. Ingham SA, Whyte GP, Pedlar C, Bailey DM, Dunman N, Nevill AM. Determinants of 800-m and 1500-m running performance using allometric models. *Med Sci Sports Exerc.* 2008;40:345-350.
12. Darveau CA, Suarez RK, Andrews RD, Hochachka PW. Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature.* 2002;417:166-170.
13. Hoppeler H, Weibel ER. Scaling functions to body size: theories and facts. *J Exp Biol.* 2005;208:1573-1574.
14. Markovic G, Vucetic V, Nevill AM. Scaling behaviour of VO₂ in athletes and untrained individuals. *Ann Hum Biol.* 2007;34:315-328.
15. Batterham AM, Jackson AS. Validity of the allometric cascade model at submaximal and maximal metabolic rates in exercising men. *Respir Physiol Neurobiol.* 2003;135:103-106.
16. Howley ET, Bassett DR, Jr., Welch HG. Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc.* 1995;27:1292-1301.
17. Suarez RK, Darveau CA, Childress JJ. Metabolic scaling: a many-splendoured thing. *Comp Biochem Physiol B Biochem Mol Biol.* 2004;139:531-541.
18. Nevill AM, Ramsbottom R, Williams C. Scaling physiological measurements for individuals of different body size. *Eur J Appl Physiol Occup Physiol.* 1992;65:110-117.
19. Kleiber M. Body size and metabolic rate. *Physiol Rev.* 1947;27:511-541.
20. Nevill AM, Jobson SA, Palmer GS, Olds TS. Scaling maximal oxygen uptake to predict cycling time-trial performance in the field: a non-linear approach. *Eur J Appl Physiol.* 2005;94:705-710.

21. Jensen K, Johansen L, Secher NH. Influence of body mass on maximal oxygen uptake: effect of sample size. *Eur J Appl Physiol*. 2001;84:201-205.
22. Nevill AM, Markovic G, Vucetic V, Holder R. Can greater muscularity in larger individuals resolve the 3/4 power-law controversy when modelling maximum oxygen uptake? *Ann Hum Biol*. 2004;31:436-445.
23. Nevill AM, Stewart AD, Olds T, Holder R. Are adult physiques geometrically similar? The dangers of allometric scaling using body mass power laws. *Am J Phys Anthropol*. 2004;124:177-182.
24. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med*. 2004;34:465-485.
25. Morgan DW, Craib M. Physiological aspects of running economy. *Med Sci Sports Exerc*. 1992;24:456-461.
26. Tartaruga MP, Brisswalter J, Peyre-Tartaruga LA, Avila AO, Alberton CL, Coertjens M, Cadore EL, Tiggemann CL, Silva EM, Kruel LF. The relationship between running economy and biomechanical variables in distance runners. *Res Q Exerc Sport*. 2012;83:367-375.
27. Kleiber M. Body size and metabolism. *Hilgardia*. 1932;6:315-353.
28. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc*. 1980;12:357-360.
29. Yoshida T, Udo M, Iwai K, Chida M, Ichioka M, Nakadomo F, Yamaguchi T. Significance of the contribution of aerobic and anaerobic components to several distance running performances in female athletes. *Eur J Appl Physiol Occup Physiol*. 1990;60:249-253.
30. Nevill A, Rowland T, Goff D, Martel L, Ferrone L. Scaling or normalising maximum oxygen uptake to predict 1-mile run time in boys. *Eur J Appl Physiol*. 2004;92:285-288.



Mechanical Work and Long-Distance Performance Prediction: the Influence of Allometric Scaling

by

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4.3.1. SUMMARY

The purpose of this study was to examine the effect of allometric scaling on the relationship between mechanical work and long-distance running performance. Fourteen recreational long-distance runners (male, mean \pm SD - age: 29 ± 7 years; body mass: 70.0 ± 10.2 kg; body height: 1.71 ± 0.07 m; maximal oxygen uptake: VO_{2max} 52.0 ± 4.9 ml \cdot kg $^{-1}$ \cdot min $^{-1}$) performed two tests: a continuous incremental test to volitional exhaustion in order to determine VO_{2max} , and a 6-minute running submaximal test at 3.1 m \cdot s $^{-1}$, during which segments in the sagittal plane were recorded using a digital camera and the internal (W_{int}), external (W_{ext}) and total (W_{tot}) mechanic work, in J \cdot kg $^{-1}$ \cdot m $^{-1}$, were subsequently calculated. The results indicated significant correlations between mechanical work and performance, however, the best correlations were observed when allometric exponents were used (respectively for W_{int} , W_{ext} and W_{tot} ; non allometric vs. allometric scaling defined by literature (0.75) or determined mathematically (0.49): $r = 0.38$ vs. $r = 0.44$ and $r = 0.50$; $r = 0.80$ vs. $r = 0.83$ and $r = 0.82$; $r = 0.70$ vs. $r = 0.77$ and $r = 0.78$). These results indicate that mechanical work could be used as a predictor of recreational long-distance performance and an allometric model may improve this prediction.

4.3.2. INTRODUCTION

An increase in participation in different forms of endurance running events has led to a need to better understand the factors that determine middle- and long-distance runners performance. Classically, the parameters of maximal oxygen uptake (VO_{2max}), running efficiency and anaerobic threshold have been used to predict this performance (Saunders et al., 2004). The energy consumption in locomotion has been extensively studied and the relationship with the mechanical work investigated (Minetti et al., 1994). A number of biomechanical factors influences on running efficiency for example the ability of muscles to store and release elastic energy by increasing the stiffness of muscles, and more efficient mechanics leading to less energy wasted on braking forces and excessive vertical oscillation

(Saunders et al., 2004).

Classically the mechanics of human locomotion have been analyzed from the mechanical work performed (Cavagna and Kaneko, 1977). This total mechanical work of locomotion (W_{tot}) is traditionally considered as the sum of the two separate entities: external mechanical work (W_{ext}) and internal mechanical work (W_{int}) (Saibene and Minetti, 2003). W_{ext} represents the work necessary to lift and accelerate the body center of mass within the environment; and it has been investigated in many different conditions and populations (Saibene and Minetti, 2003). Calculating W_{ext} involves measuring the gravitational potential energy (PE) and the kinetic energy (KE) of the body center of mass before calculating the total energy ($TE = PE + KE$) (Saibene and Minetti, 2003). The W_{ext} can be determined both by using dynamometric (direct dynamics) and motion analysis (inverse dynamics) techniques (Cavagna, 2010).

The reciprocal movements of body segments that do not affect the trajectory of the body center of mass are, to a large extent, brought about by forces internal to the body and, consequently, work associated with energy changes relative to the body center of mass correspond to W_{int} (Willems et al., 1995). Therefore, W_{int} represents the work necessary to accelerate the limbs reciprocally with respect to the body center of mass during human locomotion and it is computed using both segment movements and anthropometric parameters (Cavagna, 2010).

Some authors have also investigated how the athlete's anthropometric parameters and particularly body size can affect performance (Brisswalter et al., 1996; Ingham et al., 2008). The effect of body size for example, can be observed for Kenyan and Ethiopian runners who often dominate middle- and long-distance events in athletics. For these subjects running is systematically more economical because they generally have a smaller body size and thinner lower limbs than other runners (Foster and Lucia, 2007). Within this framework, some researchers have suggested the use of allometric scaling for efficiency assessment in order to take into account the effect of anthropometric characteristics on metabolic measures, in particular on running efficiency (Darveau et al., 2002; Nevill et al., 2004; Tartaruga et al., 2010). Running efficiency is defined as the steady-state submaximal oxygen uptake at given velocities (running economy – RE) (Saunders et al., 2004) or from energy expenditure per-unit distance (energy cost of running – Cr) (Minetti et al., 1994). These authors tried to demonstrate that an indiscriminate use of the unit $ml \cdot kg^{-1} \cdot min^{-1}$ is inappropriate for the purposes of comparing running efficiency between subjects with different body characteristics (Bergh et al., 1991) or performance level (Markovic et al., 2007), and suggested the use of $kg^{0.75}$ or kg^b , where b is the allometric or specific allometric exponent.

Within this framework, it has been well demonstrated that running efficiency depends to a large extent on locomotion mechanics (Saunders et al., 2004), therefore, to the best of our knowledge, no existing study has examined the influence of allometric scaling on the relationship between mechanical work (W_{int} , W_{ext} and W_{tot}) and the performance in long-distance runners. Thus, the purpose of this study was to examine the effect of allometric scaling on the relationships between mechanical work and the performance in recreational long-distance runners. This experiment was designed to test the hypothesis that the allometric model may improve predictions of the performance for recreational long-distance runners.

4.3.3. MATERIAL AND METHODS

4.3.3.1. PARTICIPANTS

Fourteen recreational long-distance runners (male, mean \pm SD - age: 29 ± 7 years; body mass: 70.0 ± 10.2 kg; body height: 1.71 ± 0.07 m; lower limb length: 0.80 ± 0.03 m) participated in this study. Subjects were free of any musculoskeletal, bone and joint, or cardiac and pulmonary diseases and were not taking any medications. Calculation of the sample “*n*” was carried out using the PEPI program (Version 4.0) with a power of 90%.

Prior to participation, subjects were carefully informed of the design of the study, especially the possible risks and discomforts related to the procedures. Subjects then gave their written, informed consent. The institution’s Research Ethics Committee approved the present study according to the Declaration of Helsinki.

4.3.3.2. EXPERIMENTAL PROCEDURES

Each subject took part in three experimental laboratory sessions (sample characterization, incremental treadmill running protocol and running economy test) (Figure 1), with an interval of 48 h between each session. The laboratory ambient temperature (25°C) and relative humidity (53%) were controlled according to ISO-8573-1 (International Standards). Some restrictions were imposed on the subjects: no food 3-4 h before the tests and any stimulants or intense physical activity 12 h before each evaluation.

4.3.3.3. SAMPLE CHARACTERIZATION

Body mass and height were measured using an analog medical scale (resolution of 0.1kg) and a stadiometer (FILIZOLA; Sao Paulo, Brazil) while the runners wore minimal clothing. Two experienced anthropometrists measured each subject. During the sample characterization session, all subjects participated in a familiarization exercise during which they were introduced to the process of treadmill running. In addition, all details of the care that would need to be taken while performing the exercise were explained in full.

4.3.3.4. INCREMENTAL TREADMILL RUNNING PROTOCOL

After a brief warm-up and 10 min rest (5 min sitting and 5 min standing), subjects followed a progressive protocol on a treadmill (model 250 RT, MOVEMENT; Pompéia, Brazil) with an initial velocity of 2.8 m s^{-1} , in which speed was increased by 0.28 m s^{-1} at 1 min intervals and treadmill incline was fixed at 1%. Load increments were calculated to reach $\text{VO}_{2\text{max}}$ between 8 and 14 min. The $\text{VO}_{2\text{max}}$ attainment criteria described by Howley et al. (1995) were adopted. Respiratory parameters were continually recorded using a mixing-box-type portable gas analyzer (model Aerosport VO2000, INBRAMED; Ann Arbor, MI, USA). The gas analyzer was calibrated prior to each session.

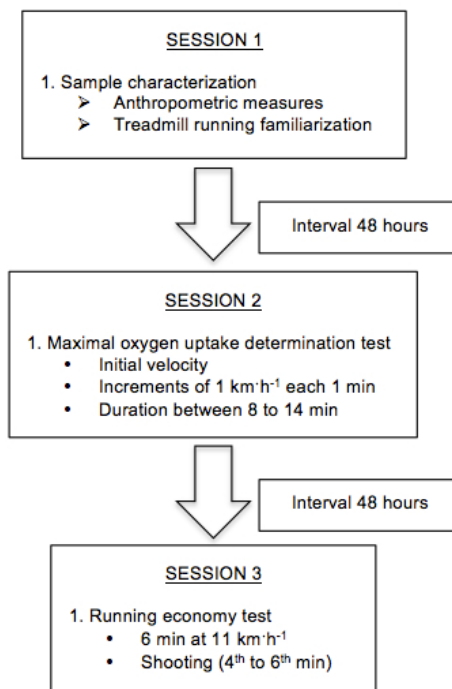


Figure 1. Experimental laboratory sessions.

4.3.3.5. RUNNING ECONOMY TEST

The running economy test consisted of a 6 min run at $3.1 \text{ m}\cdot\text{s}^{-1}$ (corresponding to $10 \pm 0,93\%$ below the velocity at the anaerobic threshold) on a treadmill. Nine reflexives hemispherical spot markers were placed on the left sagittal plane to identify the subject's segments of interest, as described by Willems et al. (1995) (Figure 2). The moving body segments were recorded during the last 20 s of the run using a digital camera (240 Hz; model EX-FH25, CASIO; Tokyo, Japan).

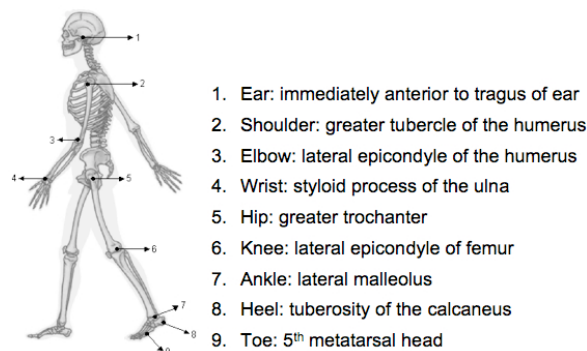


Figure 2. Localization of the retro-reflective markers.

4.2.3.6. PERFORMANCE

Performance was assessed using the fastest 10000 m run performed at the latest date in the month following laboratory testing.

4.3.3.7. ALOMETRIC SCALING

The effect of allometric scaling on the relationship between mechanical work and running performance was investigated using an allometric exponent (b) of 0.75 proposed by Bergh et al. (1991) and determined according to following general allometric equation:

$$y = ax^b, \quad (1)$$

where y is absolute VO_{2max} , x is body mass and a is a constant characteristic for the organism, which is called the allometric coefficient (Jensen et al., 2001). For determination of specific b , the exponential function was transformed into a linear function:

$$\log y = b \cdot \log x + \log a \quad (2)$$

where b is the slope of the linear regression line on a double logarithmic plot. When b is 1 (Equation 1) the relationship is isometric and when it is higher or lower than 1, the relationship is allometric.

4.3.3.8. MECHANICAL WORK

The total positive mechanical work (W_{tot}) needed to sustain locomotion comprises positive internal mechanical work (W_{int}), which is the work done to accelerate the body segments relative to body centre of mass, and positive external mechanical work (W_{ext}), which is the work done to lift and accelerate the body centre of mass relative to the environment (Cavagna and Kaneko, 1977). This was computed from mechanical energies of the body segments determined cinematically (Cavagna, 2010).

The determination of W_{int} requires computation of the instantaneous kinetic energy (KE) of each segment relative to the body centre of mass (KE_r). This was performed as follows:

$$KE_r = \frac{1}{2}mv_{ap,r}^2 + \frac{1}{2}mv_{v,r}^2 + \frac{1}{2}mK^2\omega^2 \quad (3)$$

where m is the mass of the segment, $v_{ap,r}$ and $v_{v,r}$ are the antero-posterior and vertical components of the linear velocities of each segment relative to body centre of mass velocities, K is segment radius of gyration, and ω is angular velocity of the each segment. Instantaneous KE_r of each segment within the same limb was then summed to give the kinetic energies of the upper and lower limbs, and the head-trunk. The W_{int} of each limb and of the head-trunk was then obtained by summing the positive increments of the KE curve of each limb and of the head-trunk segment separately over an integral number of strides. Consequently, the W_{int} was obtained by the sum of the internal work of each limb and the head-trunk segment. This computational scheme assumes energy transfers take place between segments of the same limb but not between limbs or between the trunk and limb.

The determination of W_{ext} requires computation of the instantaneous total mechanical energy of the body centre of mass (E_{CM}). This was performed as follows:

$$E_{\text{CM}} = Mgh + \frac{1}{2}MV_{\text{ap}}^2 + \frac{1}{2}MV_v^2 \quad (4)$$

where M is total body mass, g is gravitational acceleration ($9.81 \text{ m}\cdot\text{s}^{-2}$), h is height of the body centre of mass, V_{ap} and V_v are the antero-posterior and vertical components of the linear velocities of the body centre of mass. W_{ext} was computed by summing the positive increments in E_{CM} over the same period as for the determination of W_{int} . W_{tot} was obtained from the arithmetic sum of W_{int} and W_{ext} by applying an approximation of König's theorem of mechanics, which states that the total KE of a multilink system is made up of the KE of the segments relative to the overall centre of mass, which makes up W_{int} , and the KE of the overall centre of mass, which is included in W_{ext} (Cavagna and Kaneko, 1977).

Mechanical work measures were expressed using the same units as energy cost (Cr ; in $\text{J}\cdot\text{kg}^{-b}\cdot\text{m}^{-1}$) with b corresponding to 1, 0.75 (defined by literature) and 0.49 (determined allometrically). The conventional approach of considering only positive increments in mechanical energy (positive work) and neglecting negative work was applied. In level locomotion at a steady speed negative work is equal in magnitude but opposite in sign to positive work (and hence has no impact on comparison between groups). An inclusion of negative works would result in a network of zero which although mechanically correct is biologically meaningless and precludes determination of efficiency.

The Dvideo software (Laboratory of Biomechanics & Institute of Computing, UNICAMP; Campinas, Brazil) was used to calculate and track the bi-dimensional positions of the markers (see Figueroa et al., 2003) and, MATLAB software (Version 5.3, MathWorks, Inc.; Natick, Massachusetts, USA) was used in the reconstruction of 2D spatial model for both sagittal planes (filmed and estimated), signal processing and subsequent data over five strides. Anthropometric data of 6 rigid segments (head-trunk, upper arms, lower arms, thighs, shanks, feet) were used to compute the position of centers of mass of each segment and total body. The low-pass Butterworth filter was used with automatic cut-off frequency selection for each marker. The range of cut-off frequencies was 8 to 11 Hz. Linear and angular velocity of each segment and linear velocity of body centre of mass was determined by numerical differentiation.

4.3.3.9. STATISTICAL ANALYSIS

The Shapiro-Wilk test was used to verify the normality of the data. The Pearson product-moment correlation test was used to analyze the relationship between mechanical work and long-distance running performance. Possible differences in $VO_{2\text{max}}$ and mechanical work values, with and without the application of allometric exponents, were analyzed using one-way ANOVA with the Bonferroni Post-Hoc test based on the type of variance. Significance was accepted as $p \leq 0.05$, statistical power observed 90%, and analyses were performed in SPSS 20.0. Results are reported as means \pm SD.

4.3.4. RESULTS

The relationship between VO_{2max} and body mass in recreational long-distance runners conformed to the allometric expression (Figure 3), and significant differences in VO_{2max} values with and without the application of allometric exponents were observed (Table 1). Probably the negative relationship between body mass and VO_{2max} has been influenced by heterogeneity of body mass associated with homogeneity of the VO_{2max} values in this group.

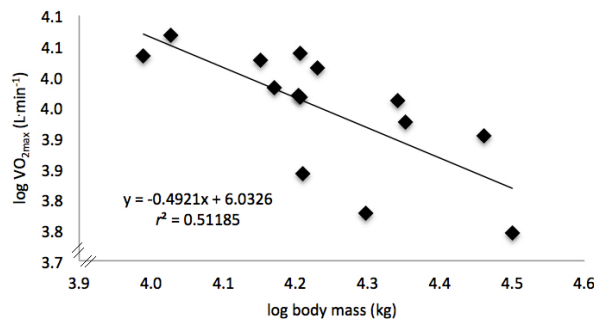


Figure 3. Relationships between maximal oxygen uptake expressed in absolute terms ($VO_{2maxabs}$) and body mass by using allometric log-linear for 14 recreational long-distance runners. Linear regression is shown with a 95% confidence interval.

Table 1. Time in 10000 m and physiological characteristics of 14 recreational long-distance runners *

Time in 10000 m (min:s)	43:38 ± 07:20
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	52.0 ± 4.9
VO_{2max} ($ml \cdot kg^{-0.75} \cdot min^{-1}$)	149.8 ± 11.1
VO_{2max} ($ml \cdot kg^{-0.49} \cdot min^{-1}$)	446.6 ± 29.9
Heart rate $_{max}$ (bpm)	189 ± 16

*Values are mean ± SD.

Significant differences were observed in mechanical work, with and without the application of allometric exponents (Table 2).

Table 2. Mechanical work at $3.1 m \cdot s^{-1}$ of 14 recreational long-distance runners *

	b = 1		b = 0.75		b = 0.49	
	Mean	SD	Mean	SD	Mean	SD
W_{int} ($J \cdot kg^{-b} \cdot m^{-1}$)	0.63	± 0.13	1.82	± 0.39	5.43	± 1.23
W_{ext} ($J \cdot kg^{-b} \cdot m^{-1}$)	1.22	± 0.13	3.52	± 0.45	10.53	± 1.62
W_{tot} ($J \cdot kg^{-b} \cdot m^{-1}$)	1.85	± 0.22	5.33	± 0.71	15.96	± 2.46

Internal Mechanical Work (W_{int}); External Mechanical Work (W_{ext}); Total Mechanical Work (W_{tot}). Allometric exponent (b). *Values are mean ± SD

Significant correlations were found between mechanical work and the performance of recreational long-distance runners, indicating that mechanical work could be a significant predictor of long-distance running performance in this population. However, the best correlations values were observed principally in W_{ext} and W_{tot} especially when using the specific allometric exponent (Table 3).

The W_{ext} showed higher values than the W_{int} ($\Delta = 51.6\%$), regardless of b values. Significant correlations were found between W_{int} and W_{ext} with W_{tot} for $b = 1$ ($r = 0.86$ and 0.81), $b = 0.75$ ($r = 0.84$ and 0.85) and $b = 0.49$ ($r = 0.83$ and 0.88).

Table 3. Relationships between mechanical works and time at 3.1 m.s⁻¹ of 14 recreational long-distance runners

	r	Equation
W_{int} ($\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$)	0.38	$y = 1240.3W_{\text{int}} + 1821.5$
W_{ext} ($\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$)	0.80	$y = 2649W_{\text{ext}} - 621.28$
W_{tot} ($\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$)	0.70	$y = 1356.3W_{\text{tot}} + 98.662$
W_{int} ($\text{J}\cdot\text{kg}^{-0.75}\cdot\text{m}^{-1}$)	0.44	$y = 492.07W_{\text{int}} + 1707.8$
W_{ext} ($\text{J}\cdot\text{kg}^{-0.75}\cdot\text{m}^{-1}$)	0.83	$y = 814.16W_{\text{ext}} - 262.39$
W_{tot} ($\text{J}\cdot\text{kg}^{-0.75}\cdot\text{m}^{-1}$)	0.77	$y = 471.62 W_{\text{tot}} + 86.151$
W_{int} ($\text{J}\cdot\text{kg}^{-0.49}\cdot\text{m}^{-1}$)	0.50	$y = 175.48W_{\text{int}} + 1648.5$
W_{ext} ($\text{J}\cdot\text{kg}^{-0.49}\cdot\text{m}^{-1}$)	0.82	$y = 220.88W_{\text{ext}} + 275.38$
W_{tot} ($\text{J}\cdot\text{kg}^{-0.49}\cdot\text{m}^{-1}$)	0.78	$y = 139.16 W_{\text{tot}} + 380.36$

Internal (W_{int}), external (W_{ext}) and total (W_{tot}) mechanical work. Running Performance in 10000-m (y). $p = 0.05$

4.3.5. DISCUSSION

The present study examined the effect of allometric scaling on the relationships between mechanical work and the performance of recreational long-distance runners. The main result of our study was the ability of the mechanical work to predict the performance in recreational long-distance runners, especially when the allometric exponents were applied.

The efficiency of locomotion is influenced not by the elastic energy storage relative to body mass, but by the elastic energy storage relative to the mechanical work of locomotion (Bullimore and Burn, 2005); an effect could be observed for example in Kenyan and Ethiopian runners that often dominate middle- and long-distance events in athletics. For these subjects running is systematically more economical because they generally have a smaller body size and thinner lower limbs than other runners (Foster and Lucia, 2007), a result that demonstrates a probable relationship between mechanical work and running performance, and justifies our findings.

This important result can also be discussed in terms of the mechanical efficiency. According to Minetti et al. (1995) humans tend to choose a stride frequency that minimizes the W_{int} and W_{ext} , which increases the mechanical efficiency and improves the running efficiency. The decrease in W_{ext} is mainly due to a reduction in vertical power, and W_{int} due to an increase in stride length. According to Willems et al. (1995) the W_{int} can be affected by external forces. The two effects considered are (i) equal and opposite vertical movements against gravity and (ii) the effect of the velocity changes of the body centre of mass. Our study also demonstrated an inverse relationship between mechanical work and performance (i. e., direct relation with the time; see Table 3) in recreational long-distance runners, proving that the mechanical work and running efficiency are two important factors in long-distance runners performance.

Previous research indicates that in walking $W_{\text{ext}} \cdot \text{km}^{-1}$ decreases with speed (Cavagna, 2010), while $W_{\text{int}} \cdot \text{km}^{-1}$ increases (Cavagna and Kaneko, 1977). Furthermore, in running, W_{int} is lower than W_{ext} , about $5.5 \text{ m} \cdot \text{s}^{-1}$, whereas at the highest speeds the reverse is true (Cavagna and Kaneko, 1977), demonstrating the importance of these mechanical variables in running performance. In our study W_{ext} showed higher values than W_{int} for $3.1 \text{ m} \cdot \text{s}^{-1}$ and strongest correlations with the performance in comparison to W_{int} , corroborating with Cavagna and Kaneko (1977). In fact, in non-fatigued running, W_{ext} , corresponding to the work necessary to lift and accelerate the body center of mass within the environment (Saibene and Minetti, 2003), has been significantly more important than W_{int} , and related to inter-individual running efficiency differences in the literature (Candau et al., 1998).

The effective mechanical advantage ($\text{EMA} = r/R$, where r is the muscle mechanical advantage and R is the ground reaction force) for muscle force production also can contribute to the understanding of the relationship between body mass and mechanical work. In a study conducted by Biewener et al. (2004), an association between EMA was verified and $\text{kg}^{0.52}$ of body mass in humans during running. A similar b value was found in our study. Biewener (1989) demonstrated that this relationship may be understood based on physiological processes and a size-dependent change in locomotor limb posture: small animals run with crouched postures, whereas larger species run more upright. By adopting an upright posture, large animals align their limbs more closely with the ground reaction force, substantially reducing the forces that their muscles must exert (proportional to body mass) and hence, the forces that their bones must resist, to counteract joint moments, resulting thus in a specific b value. According to this author, a greater energy cost during running in humans, is a consequence of a great W_{int} and W_{ext} (Minetti et al., 1994), what may be explained in part by a decrease in limb mechanical advantage.

The relationship between body mass and metabolic rate, especially the b value, has attracted the interest of biologists and healthcare professionals throughout the world (Ingham et al., 2008; Tartaruga et al., 2010). Our study verified a low specific allometric exponent in maximal metabolic rate ($b = 0.49$, Figure 3), demonstrating that the scaling behaviour of human metabolic rate is, to a great extent, dependent on the physiological state (Markovic et al., 2007). Jensen et al. (2001) showed a considerable variability of b values (0.19 to 0.92) in different sports, including running ($n = 20$; $b = 0.59$), triathlon ($n = 16$; $b = 0.24$) and walking ($n = 6$; $b = 0.19$). West et al. (1997) demonstrated that allometric scaling may be understood in terms of bases that limit supply and/or physiological processes that contribute to the regulation of a metabolic rate, as proposed later by Darveau et al. (2002). This demonstrates the existence of specific allometric exponents and is contrary to the theories initially proposed by Rubner (1883) ($b = \frac{2}{3}$) and Kleiber (1947) ($b = \frac{3}{4}$). Scaling of a maximal metabolic rate has been related to aerobic capacity of humans and other animal species; whereas in animals and untrained humans the largest species of individuals have the greatest aerobic capacity, the opposite is true for human athletes, where the smallest endurance athletes exhibit the greatest aerobic performance (Markovic et al., 2007). Thus, it is not surprising that recreational runners or animals in general exhibit differential scaling behaviour of a maximal metabolic rate compared to human athletes. Furthermore, the relationship between muscular activation

during aerobic exercise and strength measurements verified by Cadore et al. (2011) suggests that there is an interaction between running efficiency and mechanical work.

Physiologically, oxygen uptake at a given submaximal running velocity is not proportional to body mass; i.e., the oxygen uptake per kg of body mass displayed an inverse relationship to body mass (Bergh et al., 1991) and this is in agreement with data from animal studies (Taylor et al., 1982), as well as from experiments involving humans (Thorstensson, 1986). In one of the first studies that used an allometric exponent to express running efficiency, Bergh et al. (1991) found that oxygen consumption during running is better related using specific allometric exponents, for example, $\text{kg}^{-3/4}$ and $\text{kg}^{-2/3}$, than to kg^{-1} .

In mechanical terms, experimental evidence confirms that the contribution of elastic energy to the mechanical work of locomotion does not increase as rapidly with size as the mass-specific energy storage capacity, suggesting that the percentage contribution of elastic energy to the mechanical work of locomotion decreases with size. The reason for this is that the mechanical work of locomotion per kilogram of body mass is directly proportional to the distance travelled (Blickhan, 1989), so that subjects with larger body size, with their longer strides, must perform relatively more work per stride. Because each tendon can store and return elastic energy only once per stride, this greater mechanical work will tend to offset the greater elastic energy storage capacity of larger runners. Therefore, the contribution of elastic energy to the mechanical work of locomotion cannot increase with size as rapidly as the energy stored per stride, and could be greater in smaller runners, demonstrating that the relationship between body weight and mechanical parameters is not linear and suggesting the application of allometric models.

4.3.6. CONCLUSION

Existing research indicates that oxygen consumption does not increase proportionally to body mass during running activities (Bergh et al., 1991; Brisswalter et al., 1996; Nevill et al., 2004; Foster and Lucia, 2007). As such, dividing oxygen uptake by body mass may produce erroneous interpretations when comparing individuals or groups who differ in body mass. In weight-supported events, studies have indicated that mechanical efficiency, dependent on mechanical work (in $\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$), is clearly an important predictor of endurance running performance. Studies have demonstrated that allometric scaling can improve the relationship between running efficiency and performance, but the relationship between mechanical work and performance has not yet been reported in scientific literature. This study revealed that mechanical work may predict recreational long-distance performance and an allometric model may improve this prediction, suggesting that the use of allometric scaling is limited according to the aerobic capacity or morphofunctional parameters of an individual. Strategies for improving or predicting endurance running performance are yet to be developed, although it appears that allometric scales may be a common element that improves this prediction for recreational long-distance runners.

4.3.7. PRACTICAL APPLICATION

Differences in body mass account for almost 70% of the differences observed in VO_{2max} and running efficiency in recreational runners. Generally measured per unit mass basis, it reduces the obvious disparities that will be observed in runners of differing total body mass. However, while expressing VO_{2max} or running efficiency on a per unit weight basis will control for differences in total body mass, it does not eliminate the differences in body composition, demonstrates that an indiscriminate use of kg^{-1} is inappropriate to compare subjects with different body characteristics. The findings of the current study demonstrate that the allometric model is a good method to determine and compare the endurance performance prediction in recreational endurance runners; an alternative, simple and interesting method that can improve the effectiveness of aerobic training.

4.3.8. REFERENCES

- Alexander RM, Bennet-Clark HC. Storage of elastic strain energy in muscle and other tissues. *Nature*, 1977; 265: 114-117
- Bergh U, Sjodin B, Forsberg A, Svedenhag J. The relationship between body mass and oxygen uptake during running in humans. *Med Sci Sports Exerc*, 1991; 23: 205-211
- Biewener AA. Scaling body support in mammals: limb posture and muscle mechanics. *Science*, 1989; 245: 45-48
- Biewener AA, Farley CT, Roberts TJ, Temaner M. Muscle mechanical advantage of human walking and running: implications for energy cost. *J Appl Physiol*, 2004; 97: 2266-2274
- Blickhan R. The spring-mass model for running and hopping. *J Biomech*, 1989; 22: 1217-1227
- Brisswalter J, Legros P, Durand M. Running economy, preferred step length correlated to body dimensions in elite middle distance runners. *J Sports Med Phys Fitness*, 1996; 36: 7-15
- Bullimore SR, Burn JF. Scaling of elastic energy storage in mammalian limb tendons: do small mammals really lose out? *Biol Lett*, 2005; 1: 57-59
- Cadore EL, Pinto RS, Alberton CL, Pinto SS, Lhullier FL, Tartaruga MP, Correa CS, Almeida AP, Silva EM, Laitano O, Kruegel LF. Neuromuscular economy, strength, and endurance in healthy elderly men. *J Strength Cond Res*, 2011; 25: 997-1003
- Candau R, Belli A, Millet GY, Georges D, Barbier B, Rouillon JD. Energy cost and running mechanics during a treadmill run to voluntary exhaustion in humans. *Eur J Appl Physiol Occup Physiol*, 1998; 77: 479-485
- Cavagna GA. Symmetry and asymmetry in bouncing gaits. *Symmetry*, 2010; 2: 1270-1321
- Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. *J Physiol*, 1977; 268: 467-481

- Darveau CA, Suarez RK, Andrews RD, Hochachka PW. Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature*, 2002; 417: 166-170
- Figueroa PJ, Leite NJ, Barros RML. A flexible software for tracking of markers used in human motion analysis. *Comp Meth Prog Biomed*, 2003; 72: 155-165
- Foster C, Lucia A. Running economy: the forgotten factor in elite performance. *Sports Med*, 2007; 37: 316-319
- Howley ET, Bassett DR, Jr., Welch HG. Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc*, 1995; 27: 1292-1301
- Ingham SA, Whyte GP, Pedlar C, Bailey DM, Dunman N, Nevill AM. Determinants of 800-m and 1500-m running performance using allometric models. *Med Sci Sports Exerc*, 2008; 40: 345-350
- Jensen K, Johansen L, Secher NH. Influence of body mass on maximal oxygen uptake: effect of sample size. *Eur J Appl Physiol*, 2001; 84: 201-205
- Kleiber M. Body size and metabolic rate. *Physiol Rev*, 1947; 27: 511-541
- Markovic G, Vucetic V, Nevill AM. Scaling behaviour of VO₂ in athletes and untrained individuals. *Ann Hum Biol*, 2007; 34: 315-328
- Minetti AE, Ardigo LP, Saibene F. Mechanical determinants of the minimum energy cost of gradient running in humans. *J Exp Biol*, 1994; 195: 211-225
- Minetti AE, Capelli C, Zamparo P, di Prampero PE, Saibene F. Effects of stride frequency on mechanical power and energy expenditure of walking. *Med Sci Sports Exerc*, 1995; 27: 1194-1202
- Nevill A, Rowland T, Goff D, Martel L, Ferrone L. Scaling or normalising maximum oxygen uptake to predict 1-mile run time in boys. *Eur J Appl Physiol*, 2004; 92: 285-288
- Roberts TJ, Marsh RL, Weyand PG, Taylor CR. Muscular force in running turkeys: the economy of minimizing work. *Science*, 1997; 275: 1113-1115
- Rubner M. Concerning the influence of body size on energy metabolism. *Z. Biol.*, 1883; 19: 536-562
- Saibene F, Minetti AE. Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol*, 2003; 88: 297-316
- Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med*, 2004; 34: 465-485
- Tartaruga MP, Medeiros MHd, Alberton CL, Cadore EL, Peyré-Tartaruga LA, Baptista RR, Kruegel LFM. Application of the allometric scale for the submaximal oxygen uptake in runners and rowers. *Biol Sport.*, 2010; 27: 297-300

- Taylor CR, Heglund NC, Maloiy GM. Energetics and mechanics of terrestrial locomotion. I. Metabolic energy consumption as a function of speed and body size in birds and mammals. *J Exp Biol*, 1982; 97: 1-21
- Thorstensson A. Effects of moderate external loading on the aerobic demand of submaximal running in men and 10 year-old boys. *Eur J Appl Physiol Occup Physiol*, 1986; 55: 569-574
- West GB, Brown JH, Enquist BJ. A general model for the origin of allometric scaling laws in biology. *Science*, 1997; 276: 122-126
- Willems PA, Cavagna GA, Heglund NC. External, internal and total work in human locomotion. *J Exp Biol*, 1995; 198: 379-393

Article

The Relationship between Mechanical Efficiency and Long-distance Running Performance

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4.4.1. SUMMARY

The purpose was to examine the contribution of mechanical work and cost of running (C_r) on mechanical efficiency of running locomotion (ME_r). Thirteen long-distance runners (male, age: 33 ± 8 years; stature: 180.1 ± 5.3 cm; maximal oxygen uptake - VO_{2max} : 52.8 ± 4.6 ml·kg⁻¹·min⁻¹) performed a continuous incremental test to determine VO_{2max} , one running economy (RE) tests at treadmill speeds divided into three intermittent submaximal exercises representing 50%, 70% and 90% of vVO_{2max} and, a supra-maximal test until volitional exhaustion at 110% of vVO_{2max} to assess the anaerobic energy expenditure (AnE). Performance in 1000 m was measured on the track. ME_r was expressed as the ratio between the total mechanical work (W_{tot}), determined cinematically by sum of internal (W_{int}) and external (W_{ext}) mechanical work, and C_r . The C_r showed relationship with ME_r (40.1%), followed by W_{ext} (33.8%) and W_{int} (26.1%). The result with two independent variables were similar, i.e. W_{tot} (62.5%) and C_r (37.5%). ME_r at 3.61 m·s⁻¹ was 58.5% when AnE was included in the calculation of metabolic power. When AnE was excluded, ME_r was 65.5%. ME_r is better predicting by mechanical work in comparison to C_r , and overestimated when AnE is not considered in the computation of metabolic power.

4.4.2. INTRODUCTION

The increase in participation in different forms of endurance running events over the last few decades has led to the need to better understand the factors that determine endurance performance according to each specific profile of endurance event. Classically, the parameters of maximal oxygen uptake (VO_{2max}), anaerobic threshold (AT), running economy (RE) and mechanical efficiency (ME) have been used to predict athletes' performance in middle- and long-distance running events [1-3].

ME reflect the chemical conversion of metabolic energy to mechanical work. In the muscle, metabolic energy is generated through the ATPase-catalyzed hydrolysis of adenosine triphosphate (ATP) to adenosine diphosphate. The total useable energy from the ATPase reaction allows actin-myosin cross-bridge formation and thus enables muscle contraction. The rate of ATP hydrolysis is reflective of the metabolic energy cost and is a key determination of exercise intensity. The ME concept represents a unique way of understanding the complexities of the bioenergetics of human locomotive forms such as running [4].

ME of running locomotion (ME_r), expressed as the ratio between the total mechanical work (W_{tot}) - traditionally considered as the sum of internal (W_{int}) and external (W_{ext}) mechanical work [5, 6] - and energy expenditure, has been reported between 40% and 70% [4], with intraindividual variation between 3% and 11% [7]. These variations have been associated with RE, which is considered to be the submaximal oxygen uptake ($VO_{2submax}$) per unit body weight required for performing a given task [8, 9]. According to initial reports by Daniels [10], RE can vary by more than 30% among runners who have a similar $\dot{V}O_{2max}$.

The first well known study on ME_r was published in 1927 by Furusawa et al. [11]. In this study, W_{tot} during sprinting was estimated by calculating the propelling force (i. e. 0.7 multiplied by body mass and, subsequently by distance), while energy cost was estimated by directly measuring oxygen uptake during the recovery period. Using this method, Furusawa et al. [11] reported ME_r values of 35% to 45%. Currently, the W_{tot} accomplished during running locomotion has been estimated using kinematic methods [12]. This approach is based on the theory that the changes in kinetic and potential energy resulting in W_{tot} (the time integral of mechanical power) [4].

Various physiological and morphological factors, such as VO_{2max} [13], AT [4], cost of running (C_r) [14] and body weight [15], have been proven to influence ME_r and, consequently, numerous investigations that focus on these dynamic parameters have been published. Likewise, mechanical factors, such as W_{int} and W_{ext} , have been identified as playing an important role in variations of ME_r . For example, previous research indicates that during running $W_{ext} \cdot km^{-1}$ and $W_{int} \cdot km^{-1}$ are modified with speed [16]. Furthermore, according to Minetti et al. [17], humans tend to choose a stride frequency that minimizes the W_{int} and W_{ext} ; this serves to increase the ME_r and improve the RE. The decrease in W_{ext} is mainly due to a reduction in vertical power, and W_{int} due to an increase in stride length.

However, despite the fact that the impact that ME_r has on running performance has been recognized since the 1920s, the relationships between mechanical work, specifically W_{int} and W_{ext} , and ME_r in long-distance running athletes has been poorly examined. Similarly, the effects of body size and anaerobic contribution on the relationship between C_r and ME_r , consequently running performance, remains relatively ignored in existing scientific literature compared to other performance factors, in particular, (1) a high value of VO_{2max} ; (2) a high fraction of VO_{2max} , which can be sustained throughout the competition; and (3) a better RE [18]. Authors tried to demonstrate that an indiscriminate use of the unit $ml \cdot kg^{-1} \cdot min^{-1}$ is inappropriate for the purposes of comparing RE between subjects with different body characteristics [19] or performance level [20], and suggested the use of $kg^{0.75}$ or kg^b , where b is the allometric or specific allometric exponent. In addition, an estimate of anaerobic energy

expenditure should be considered in the computation of metabolic power when determining ME_r [4].

Therefore, to achieve a better understanding of the relationships between ME_r and long-distance running performance, we analyzed the influence of mechanical work and C_r on ME_r on long-distance runners, both morphologically and metabolically. Our hypothesis was that ME_r , morphologically independent, is overestimated with the exclusion of anaerobic energy expenditure and, consequently, the relationship between ME_r and long-distance running performance is modified during treadmill running. Furthermore, recent indirect evidence that energy is partly conserved in human running thanks to an elastic bounce of the body [21] allows us believe that the ME_r is strongly influenced by the mechanical work, particularly external mechanical work. We hypothesized that the greater ratio mechanical work/energy expenditure, ME_r , ascribed to major amount of elastic energy stored and high economy, would be related to a better performance in long-distance running performance.

4.4.3. EXPERIMENTAL SECTION

4.4.3.1. SUBJECTS

Thirteen long-distance runners (male, mean \pm *SD* – age: 33 ± 8 years; stature: 180.1 ± 5.3 cm; body mass: 76.4 ± 8.6 kg; body fat: $12.9 \pm 2.7\%$; training volume: 51.0 ± 5.5 km \cdot week $^{-1}$; VO_{2max} : 52.8 ± 4.6 ml \cdot kg $^{-1}$ \cdot min $^{-1}$) without any known orthopedic, neuromuscular, or cardiovascular problems volunteered to participate in this investigation. Calculation of the sample “*n*” was carried out using a power of 90%. Subjects read and signed a consent form before participating in the study, which was approved by the local university’s Institutional Ethics and Research Committee. All experimental procedures were conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki).

4.4.3.2. EXPERIMENTAL PROCEDURES

Subjects underwent three experimental laboratory sessions (sample characterization; incremental treadmill running protocol test; running economy and supra-maximal tests) (see Figure 1). An interval of 48 h took place between each session. The laboratory ambient temperature (25°C) and relative humidity (53%) were controlled according to ISO-8573-1 (International Standards). Several restrictions were imposed on the subjects: no food 3-4 h before the tests and any stimulants or intense physical activity 12 h before each evaluation.

4.4.3.3. SAMPLE CHARACTERIZATION

Anthropometric parameters were recorded using scales and a stadiometer (Urano Model PS-180, Porto Alegre, Rio Grande do Sul, Brazil) while the runners wore minimal clothing. The percentage of body fat was calculated using the Siri equation [22]. Subjects were familiarized

with 10-min of treadmill running (Quinton, Seattle, USA) at $2.22 - 3.05 \text{ m s}^{-1}$ and 1% grade, with specific ergospirometric accessories.

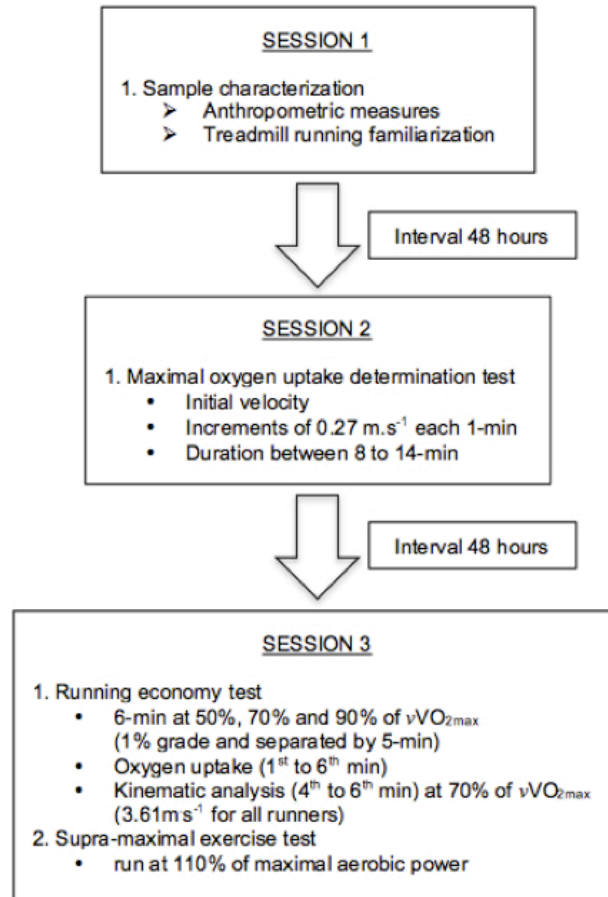


Figure 1. Laboratory sessions.

4.4.3.4. INCREMENTAL TRADMILL RUNNING PROTOCOL TEST

After a brief warm-up and 10-min rest (5-min sitting and 5-min standing), each subject performed a continuous velocity graded test on a treadmill to exhaustion to determine AT, $\text{VO}_{2\text{max}}$ and the associated velocities (v). The protocol was similar to that outlined by Tartaruga et al. [9], whereby running tests were performed on a motorized treadmill that retained a 1% grade. Subjects performed an initial velocity of 2.77 m s^{-1} and this was increased by 0.27 m s^{-1} at 1-min intervals. Load increments were calculated to reach $\text{VO}_{2\text{max}}$ between 8 and 14-min. $\text{VO}_{2\text{max}}$ was identified as the highest value to the following three criteria: maintenance in $\text{VO}_{2\text{max}}$ with increase in the exercise intensity, subject could no longer sustain the workload, and respiratory-exchange ratio ≥ 1.0 . To determine AT, ventilatory equivalents slopes for oxygen and carbon dioxide [ventilation (VE) / VO_2 and VE / VCO_2] were used. Three independent reviewers assessed the AT graphs, determined the corresponding break points by visual inspection in a blind procedure.

Breath-by-breath respiratory parameters were recorded using a metabolic cart (MGC Model CPX/D, St. Paul, USA). Before each test, the device was calibrated according to the manufacturer's instructions. O₂ and CO₂ analyzers were calibrated using ambient air and sample gas references of 16% O₂ and 4% CO₂. The flow sensor was also calibrated using a syringe of known volume (3.00 L).

4.4.3.5. RUNNING ECONOMY AND SUPRA-MAXIMAL TEST



After an initial warm-up period of 5-min at 30% of $\dot{V}O_{2\max}$, each subject performed one RE test divided into three intermittent submaximal exercises. Each submaximal exercise consisted of a single 6-min exercise bout at treadmill speeds representing 50% ($2.7 \pm 0.2 \text{ m}\cdot\text{s}^{-1}$), 70% (corresponding to $3.61 \text{ m}\cdot\text{s}^{-1}$ for all subjects and $13 \pm 4.9\%$ of anaerobic threshold) and 90% ($4.8 \pm 0.3 \text{ m}\cdot\text{s}^{-1}$) of $\dot{v}O_{2\max}$ at 1% grade and 5-min rest between each intensity. A supra-maximal test was performed until voluntary exhaustion at 110% of maximal aerobic velocity ($\dot{v}W_{\max}$) after 5-10-min of RE test.

4.4.3.6. METABOLIC DATA

For each session of treadmill running, metabolic power (in J s^{-1}) was obtained while considering contributions from both aerobic (AE; from $\text{VO}_{2\text{max}}$) and anaerobic (AnE; from accumulated O_2 -deficit) energy expenditure as described in detail by Reis and Carneiro [23] and Keir et al. [4]. AnE was derived from the accumulated O_2 -deficit, as outlined by Medbo et al. [24].

For the determination of C_r (or RE), the net VO_2 values, which were obtained by subtracting pre-exercise standing VO_2 from gross VO_2 and converting the result to joules using an energetic equivalent of $20.9 \text{ J mL}^{-1} \text{O}_2$, were determined based on the mean VO_2 values recorded during the last minute at 3.61 m s^{-1} . C_r , defined as the energy cost of moving 1 kg of body mass 1 m ($\text{J kg}^{-1} \text{m}^{-1}$), was then obtained by dividing the net energy expenditure ($\text{J kg}^{-1} \text{min}^{-1}$) by speed (m min^{-1}).

4.4.3.7. KINEMATIC DATA

Kinematic data were recorded for the last 20-sec at 3.61 m s^{-1} and W_{int} and W_{ext} were assessed using three-dimensional digital images. A total of five strides (corresponding to the last five strides recorded in the last minute before session completion) were analyzed for each subject. Images were recorded via four digital cameras (Casio Model EX-FH25, Okinawa, Japan), which sampled at 240 Hz. Images were synchronized using Dvideow software [25]. For all subjects, cameras were calibrated in a space equal to 2 m^3 .

Eighteen retro-reflective markers were attached bilaterally to landmarks that defined segment extremities (immediately anterior to tragus of ear, shoulder, elbow, wrist, greater trochanter, lateral epicondyle of femur, lateral malleolus, calcaneus, and 5th metatarsal head). Dvideo software was used to calculate and track the three-dimensional positions of the markers. MATLAB software (MathWorks, Version 5.3, Paris, France) was used to perform signal processing. A low-pass Butterworth filter was used with automatic cut-off frequency selection for each marker. The range of cut-off frequencies was 8 to 11 Hz. Linear and angular velocity of each segment and linear velocity of body centre of mass was determined by numerical differentiation. Values for segment mass, centre of mass position and radius of gyration were taken from standard tables that were produced by Dempster et al. [26].

W_{tot} individual (in $\text{J kg}^{-1} \text{m}^{-1}$) was obtained by calculating the sum of W_{int} and W_{ext} considering the energy transfer between segments [5, 6]. W_{int} represents the work necessary to accelerate the limbs reciprocally with respect to the body centre of mass during human locomotion [14] and W_{ext} represents the work necessary to lift and accelerate the body centre of mass within the environment [6].

Positive W_{int} was computed using the method presented by Cavagna and Kaneko [5]. In order to account for the kinetic energy changes of the segments for which the movements do not affect the position of the overall centre of mass (i.e. symmetrical limb displacements), König's theorem from mechanics was applied. This theorem states that the total kinetic energy (KE) of a multi-link system can be divided into two parts: (a) the KE of the segments arising

from their change of speed with respect to the overall centre of mass, and (b) the KE of the overall centre of mass. Other details of the experimental design were reported by Minetti et al. [27]. Positive W_{ext} and negative W_{ext} were obtained by summing the increments and the decrements respectively of the total energy (gravitational potential energy (PE) + horizontal KE + vertical KE) curve of the body centre of mass position *versus* time. The W_{ext} was computed as the sum of positive W_{ext} [28, 29].

The percentage efficiency of work production was computed as follows:

$$ME_r = \frac{W_{\text{tot}}}{C_r} \times 100 \quad (1)$$

4.4.3.8. PERFORMANCE

Performance was assessed from the best performance (fastest times) in long distance events corresponding to 1000-m performed at the latest in the month following laboratory testing. The testing was performed in the morning hours (between 9 a.m. and 11 a.m.) in thermo-neutral conditions [20].

4.4.3.9. ALLOMETRIC NORMALIZATION

To understand how the morphological aspects affect the C_r and W_{tot} , allometric normalization was employed. Allometry is the study of the relationship between size, shape and function in organisms and was first outlined by Max Rubner in 1883, Otto Snell in 1892, D'Arcy Thompson in 1917, Julian Huxley and Max Kleiber in 1932 [30]. Allometric scaling can be described using the general equation $y = ax^b$. This can be transformed into a logarithmic linear function ($\log y = b \cdot \log x + \log a$), where y is the absolute metabolic rate during submaximal and maximal exercise condition, x is body mass, b is the allometric or scaling exponent and a is a constant characteristic for the organism, called the allometric coefficient [31, 32].

4.4.3.10. STATISTICAL ANALYSIS

Descriptive statistic calculations are presented as means and $\pm SD$. Normality of the data was assessed using the Shapiro-Wilk's test. Pearson's product-moment correlation was used to investigate the relationships without cause-effect between ME_r and mechanical (W_{intr} , W_{ext} and W_{tot}) or metabolic parameters (aerobic cost of running, $C_{r\text{AE}}$; anaerobic cost of running, $C_{r\text{AnE}}$; total cost, C_r), with and without the application of specific allometric exponents (related to maximal and submaximal metabolic rates); and between ME_r and long-distance running performance. We performed a multiple linear regression analysis to investigate the influence of each mechanical and metabolic parameter on ME_r . An analysis of covariance (ANCOVA) model was performed to determine allometric exponents and repeated measures analysis of

variance, with Bonferroni's post-hoc test was used to assess the statistical differences inter-parameters. Analyses were performed using SPSS v.20.0, with $\alpha = 0.05$.

4.4.4. RESULTS AND DISCUSSION

Anthropometric data, as well as results from the incremental treadmill running session and performance from 10000-m, are presented in Table 1. The allometric relationships between human metabolic rate during maximal and submaximal exercise condition with the body mass are presented in Table 2.

Table 1 - Performance value, physiological characteristics and results from incremental treadmill running session of 13 long-distance runners. Mean \pm SD.

Performance - 10 km (min:sec)	43:40 \pm 02:27
Age (years)	33.3 \pm 8.4
Height (cm)	180.1 \pm 5.3
Body mass (kg)	76.4 \pm 8.6
Body fat (%)	12.9 \pm 2.7
AT (ml·kg ⁻¹ ·min ⁻¹)	43.5 \pm 3.0
vAT (m·s ⁻¹)	4.36 \pm 0.3
VO _{2max} (ml·kg ⁻¹ ·min ⁻¹)	52.8 \pm 4.6
vVO _{2max} (m·s ⁻¹)	5.26 \pm 0.3

Note: anaerobic threshold (AT) and velocity (v).

Table 2. Logarithmic linear relationships between body mass (BM) and metabolic rate (MR) during maximal and submaximal exercise condition of 13 long-distance runners.

Metabolic condition	a	b	r	p
BM (kg) vs. VO _{2max} (L·min ⁻¹)	-1.89	0.76	0.69	0.009
BM (kg) vs. RE (L·min ⁻¹)	-2.60	0.84	0.93	< 0.001

Note: scaling constants (a), body mass scaling exponents (b), correlation coefficients (r) and significance levels (p).

Significant correlations ($p < 0.05$) between VO_{2max} and performance were observed with and without the allometric exponent normalization (respectively for $b = 0.76$, $r = -0.86$; $b = 0.84$, $r = -0.87$; $b = 1$, $r = -0.91$). Likewise, significant correlations were found between C_r , W_{ext} and W_{tot} and the performance (see Table 3), indicating that these economical parameters may affect long-distance running performance. The specific relationship between mechanical work and performance is affected by allometric scaling. Significant correlations ($p < 0.05$) between mechanical work (W_{ext} and W_{tot}) and C_r were observed with and without the allometric exponent normalization (respectively for W_{ext} : $b = 0.76$, $r = -0.59$; $b = 0.84$, $r = -0.67$; $b = 1$, $r = -0.75$ and W_{tot} : $b = 0.76$, $r = -0.47$; $b = 0.84$, $r = -0.57$; $b = 1$, $r = -0.67$).

Table 3 - Metabolic and mechanical parameters at 3.6 m·s⁻¹ and relationships with the VO_{2max} and performance (10000-m) of 13 long-distance runners.

variables	mean	VO _{2max}		performance	
		<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
C_r (J·kg ^{0.76} ·m ⁻¹)	8.82 ± 0.23	-0.64	0.019*	0.85*	< 0.001
C_r (J·kg ^{0.84} ·m ⁻¹)	6.25 ± 0.17	-0.68	0.010*	0.84*	< 0.001
C_r (J·kg ⁻¹ ·m ⁻¹)	3.08 ± 0.10	-0.74	0.004*	0.84*	< 0.001
W_{int} (J·kg ^{0.76} ·m ⁻¹)	1.26 ± 0.18	-0.16	0.595	0.11	0.709
W_{int} (J·kg ^{0.84} ·m ⁻¹)	0.89 ± 0.13	-0.17	0.570	0.15	0.622
W_{int} (J·kg ⁻¹ ·m ⁻¹)	0.44 ± 0.06	-0.21	0.501	0.18	0.554
W_{ext} (J·kg ^{0.76} ·m ⁻¹)	3.90 ± 0.21	-0.55	0.052	0.58*	0.036
W_{ext} (J·kg ^{0.84} ·m ⁻¹)	2.77 ± 0.15	-0.55	0.053	0.64*	0.019
W_{ext} (J·kg ⁻¹ ·m ⁻¹)	1.36 ± 0.08	-0.59*	0.034	0.71*	0.007
W_{tot} (J·kg ^{0.76} ·m ⁻¹)	5.16 ± 0.23	-0.64*	0.019	0.64*	0.019
W_{tot} (J·kg ^{0.84} ·m ⁻¹)	3.66 ± 0.16	-0.65*	0.017	0.71*	0.006
W_{tot} (J·kg ⁻¹ ·m ⁻¹)	1.80 ± 0.08	-0.68*	0.010	0.77*	0.002

Note: *Significantly correlations ($p < 0.05$). Significant differences were verified for the different normalization conditions (i. e. body mass scaling exponent (b) = 0.76 corresponding to maximal metabolic rate; $b = 0.84$ corresponding to submaximal metabolic rate; $b = 0.84$ corresponding to traditional normalization) ($p < 0.05$).

The metabolic power significantly increased with relative speed: 667 ± 128, 968 ± 92, 1278 ± 142 and 1403 ± 163 J·s⁻¹ for 50%, 70%, 90%, and 110% of vVO_{2max}, respectively (see Figure 2).

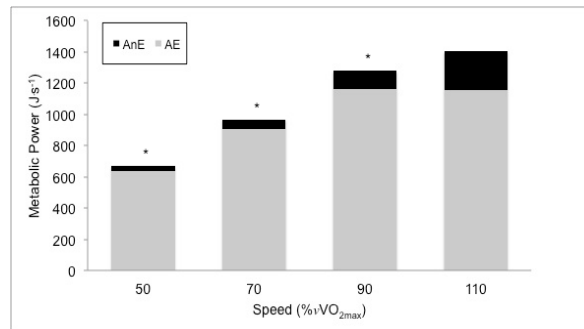


Figure 2. Relative contribution of aerobic-energy (AE) and anaerobic-energy (AnE) metabolic pathways at 4 relative running speeds of 13 long-distance runners. *Significant difference in anaerobic power (relative to total metabolic power) from 110% velocity at VO_{2max} (vVO_{2max}) ($p < 0.05$).

AE significantly increased as speed progressed from 50% to 90% of vVO_{2max} ($p < 0.05$ for all pairwise comparisons). However, there was no difference in AE measured in the 90% and 110% vVO_{2max} condition ($p = 0.890$). The difference in metabolic power observed between 90% and 110% vVO_{2max} was explained, rather, by a significant increase in AnE between these two speeds (117 to 249 J·s⁻¹). Approximately, 95.3% of metabolic power was attributed to AE and 4.7% to AnE for 50% vVO_{2max}, 93.4% and 6.6% for 70% vVO_{2max}, 90.9% and 9.1% for 90% vVO_{2max}, and 82.1% and 17.9% for 110% vVO_{2max}.

ME_r at 3.61 m·s⁻¹ (70% of vVO_{2max}) was 58.5 ± 3.2% when AnE was included in the calculation of metabolic power, independently of b value. When AnE was excluded, ME_r was 65.5 ± 4.6%; $p < 0.001$. The data indicates that ME_r is independent of morphological aspects and suggests an overestimation when AnE is not considered in the computation of metabolic power. Significant correlation between ME_r and performance was observed ($r = 0.59$, $p =$

0.035), indicating that these variables affect long-distance running performance. A significant correlation between C_r , W_{ext} and W_{tot} with the ME_r were verified (see Figure 3).

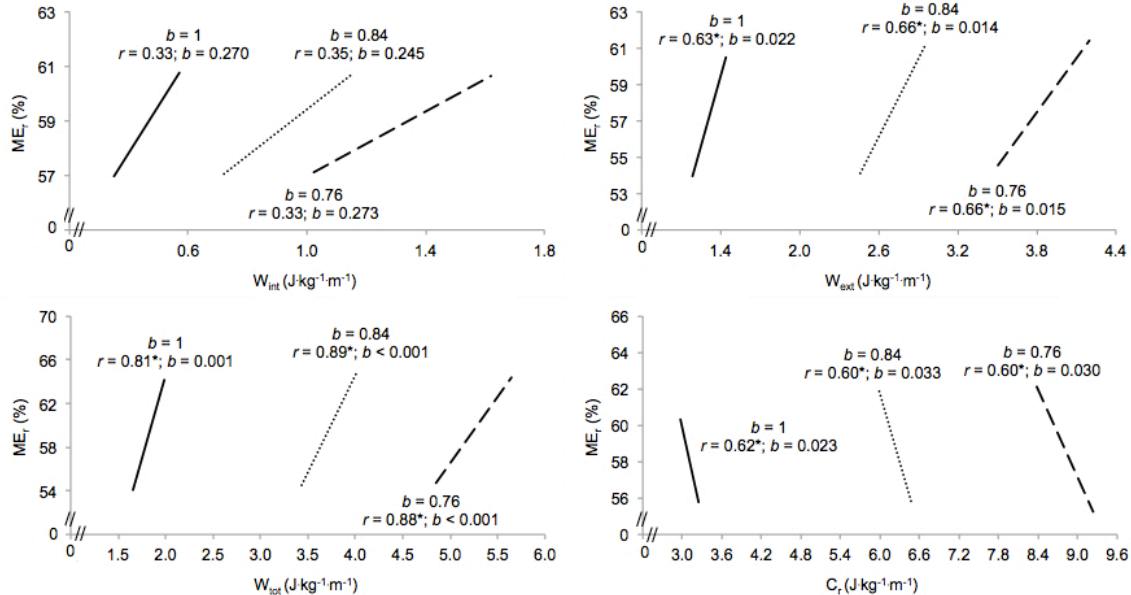


Figure 3. Relationships between internal (W_{int}), external (W_{ext}), total (W_{tot}) mechanical work and cost of running (C_r) with the mechanical efficiency (ME_r) at 3.6 m s^{-1} of 13 long-distance runners. * $p < 0.05$.

The relationship between the independent variables (C_r , W_{int} , W_{ext} and W_{tot}) and dependent variable (ME_r) was verified using multiple linear regression analysis (Table 4).

Table 4 - Results of the multiple linear regression analysis.

Option	Model	Adjusted R Square	Std. Error of the Estimate	Sig.	Independent Variables
A	1	0.337	2.5981	< 0.05	W_{ext}
	2	0.591	2.0397	< 0.05	W_{ext} and W_{int}
	3	0.998	0.1453	< 0.05	W_{ext} , W_{int} and C_r
B	1	0.624	1.9564	< 0.05	W_{tot}
	2	0.998	0.1589	< 0.05	W_{tot} and C_r

Note: external mechanical work (W_{ext}), internal mechanical work (W_{int}) and cost of running (C_r).

$$ME_r = 57.834 - 18.770(C_r) + 31.947(W_{int}) + 32.648(W_{ext})$$

$$ME_r = 57.254 - 18.698(C_r) + 32.663(W_{tot})$$

The overall predictive power of the model was 99.8%, with an estimated error of 0.15. The C_r showed the strongest relationship with ME_r (40.1%), followed by W_{ext} (33.8%) and W_{int} (26.1%) for option A. The power of the model and estimated error with two independent variables (C_r and W_{tot} ; option B) were similar, i.e. W_{tot} (62.5%) and C_r (37.5%).

The aim of the current study was to analyze the influence of mechanical work and C_r on ME_r on the performance of long-distance runners, both morphologically and metabolically. The key findings were: (1) W_{tot} and C_r are strong predictors of ME_r ; (2) the exclusion of AnE in the calculation of metabolic power yielded significantly greater values of ME_r ; (3) C_r is not affected by allometric scaling, contrary to the correlations between W_{ext} and W_{tot} with long-distance running performance; (4) ME_r is not affected by allometric scaling. To the best of our

knowledge, no study has examined the relationships between mechanical work, specifically W_{int} and W_{ext} in separated, and ME_r in long-distance running athlete, as well as the effects of body size and anaerobic contribution in ME_r and running performance.

The first finding of this study was an observed change in the metabolic rate and body mass relationship as an organism moves in maximal and submaximal metabolic conditions. In the maximal metabolic condition, we observed an allometric exponent of 0.76 and, in the submaximal condition, a b value of 0.84. Similar scaling behaviour of metabolic rate in athletic population was also observed by Paterson et al. [33], Bergh et al. [19] and Markovic et al. [20], who reported submaximal metabolic rate scales with higher mass scaling exponent than maximal metabolic rate. These results suggest that the cardiovascular system of smaller athletes has a greater capacity to raise metabolic rate above those at rest, not larger ones, as suggested by Weibel [34] and experimental results [35, 36].

C_r showed significant positive correlation with long-distance running performance, and the allometric model did not affect this relationship. RE, which is classically assessed in terms of the energy required to run at a given submaximal velocity [37] or the metabolic energy expended per unit of distance [38], is an important factor that can be used to predict middle- and long-distance running performance [9, 39-42]. According to initial reports by Daniels [10], RE can vary by more than 30% among runners who have a similar $VO_{2\text{max}}$, and its relative contributions are not affected by alterations to body weight [43, 44]. However, a consensus has not yet been reached on this argument. Bergh, Sjodin, Forsberg and Svedenhag [19] found that oxygen consumption during running is better related using specific allometric exponents, for example, $\text{kg}^{-3/4}$ and $\text{kg}^{-2/3}$, than to kg^{-1} . Another possible confusing factor in the use of allometric scaling to assess oxygen consumption could be due to differences in aerobic capacity among subjects (i.e. untrained or moderately trained vs. runners that compete at a high level) [20]. In a recent study that analyzed the allometric relationship between oxygen consumption (ranging from rest to maximal condition) and body mass in trained and untrained individuals, Markovic et al. [20] found that the allometric model may be useful as a means of assessing oxygen consumption in untrained individuals, whereas it has no effect on trained athletes.

The mechanical work, especially the W_{ext} and W_{tot} , showed significant correlations with long-distance running performance, and these relationships were affected by allometric model. Effects of body dimensions on mechanical work are probably due to the influence of body size on biomechanical variables of running technique [9]; for example, the angle of contact with the ground (i.e. the angle of the link between the point of contact and the hip, relative to the vertical) and its relationship with the deceleration of the body each step and, consequently, with mechanical work [45].

During running, W_{int} is 15-20% lower than the W_{ext} , about $5.5 \text{ m} \cdot \text{s}^{-1}$, whereas at the highest speeds the reverse is true [5, 11]; this demonstrates the important impact that these mechanical variables have on running performance. In our study, the W_{ext} exhibited greater values than the W_{int} for $3.61 \text{ m} \cdot \text{s}^{-1}$ and stronger correlations with the performance; this corroborates with the work of Cavagna and Kaneko [5]. In non-fatigued running, the W_{ext} corresponding to the work necessary to lift and accelerate the body center of mass within the

environment [6], has been significantly more important than the W_{int} , and related to inter-individual RE differences in the literature [46]. In fact, runners with better RE may present higher values of mechanical work and, consequently, better ME_r [47].

The relative contributions of energy release from AnE and AE that were observed for each percentage of vVO_{2max} (Figure 2) are consistent with previous reports [4, 48]. Estimating the accumulated O_2 -deficit is a noninvasive indirect method of obtaining AnE during running bouts [24] and has been used in the past to determine AnE during brief exercise sessions. While it is acknowledged that the accumulated O_2 -deficit method used in the current study is not without its shortcomings, it remains the best noninvasive method of quantifying AnE during a session of constant-speed exercise [49].

Using the proposed model, ME_r was significantly different from 50% vVO_{2max} at the 90% and 110% relative speeds; however, no other differences were observed with respect to speed. The ME_r values during treadmill running obtained within the current investigation are similar in magnitude to those obtained in existing literature (~40-75%) [4, 5, 49]. The maximal value of ME_r of the contracting muscle during locomotion has been considered to be approximately 30% [47]. The high value of ME_r (~55-65%) obtained in the current study may stem from the kinematic method applied in quantifying mechanical power [4]. Nevertheless, the contribution of AnE expenditure cannot be overlooked when calculating the metabolic power component of treadmill running and likely other forms of human locomotion.

The principal finding of this study concerned the strong relationships between metabolic and mechanical parameters and ME_r . Significant positive correlations between mechanical work and ME_r , and an inverse correlation between C_r and ME_r , were verified (see Figure 3). The multiple linear regression analysis (Table 4) showed that mechanical work and C_r are predictors of ME_r , with an overall predictive power of 99.8%.

In adults, ME_r increases steadily with speed, from about 45% at $2.5 \text{ m}\cdot\text{s}^{-1}$ to 65% at $5.5 \text{ m}\cdot\text{s}^{-1}$, assuming a C_r of $4.18 \text{ J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ (i.e. $1 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$), suggesting that positive work derives mainly from the passive recoil of muscle elastic elements and, to a lesser extent, from the active shortening of the contractile machinery [5]. Furthermore, changes in the C_r can increase or decrease the ME_r , depending upon the effect of the zero-speed intercept [45]. The ability to convert chemical energy into positive work is equal in children and adults [45], and the value of the ME_r is independent of age and body size [50]. During steady-state running, some of the potential and the kinetic energy absorbed during negative work is stored and recovered during positive work (W_{tot}) [5, 45], and this can justify the strong relationship between W_{tot} and ME_r that was verified during our study. In fact, the efficiency of positive work production during running is greater than the metabolic efficiency [50], principally during treadmill running [3].

4.4.5. CONCLUSION

Determining a “true” efficiency value for running is difficult, since this involves many elusive factors such as mechanical energy transfer, elastic energy utilization, and energy cost [11]. However, regardless of the method used to calculate the ME_r , it seems that the W_{tot} and C_r are the key predictor variables. Likewise, the ME_r is dependent of RE. Furthermore, we

demonstrated in the current study that estimates of AnE should be taken into account when calculating the metabolic power of the ME_r model. AnE contributes a significant amount of energy in treadmill running at speeds ranging from submaximal to supramaximal. This contribution reduces the ME_r values, suggesting that an estimate of AnE should be considered in the computation of metabolic power when determining ME during treadmill running, as its exclusion leads to overestimations of ME_r values, as demonstrated by Keir et al. [4]. Finally, in weight-supported events, studies have indicated that mechanical efficiency, dependent of mechanical work (in J·kg⁻¹·m⁻¹), is clearly an important predictor of endurance running performance. Studies have demonstrated that allometric scaling can improve the relationship between ME_r and performance. This study revealed that W_{tot} may predict recreational long-distance performance and an allometric model may decrease this prediction, suggesting that the use of allometric scaling is limited according to the morphological or biomechanical parameters of a long-distance runner.

4.4.6. REFERENCES

1. Midgley, A.W.; McNaughton, L.R.; Jones, A.M. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Med.* 2007, 37, 857-880.
2. Sjodin, B.; Svedenhag, J. Applied physiology of marathon running. *Sports Med.* 1985, 2, 83-99.
3. Kyrolainen, H.; Komi, P.V.; Belli, A. Mechanical efficiency in athletes during running. *Scand J Med Sci Sports.* 1995, 5, 200-208.
4. Keir, D.A.; Zory, R.; Boudreau-Lariviere, C.; Serresse, O. Mechanical efficiency of treadmill running exercise: effect of anaerobic-energy contribution at various speeds. *Int J Sports Physiol Perform.* 2012, 7, 382-389.
5. Cavagna, G.A.; Kaneko, M. Mechanical work and efficiency in level walking and running. *J Physiol.* 1977, 268, 467-481.
6. Saibene, F.; Minetti, A.E. Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol.* 2003, 88, 297-316.
7. Morgan, D.W.; Baldini, F.D.; Matin, P.E. Day-to-day stability in running economy and step length among well-trained male runners (abstract). *Int J Sports Med.* 1987, 8, 242.
8. Cavanagh, P.R.; Kram, R. The efficiency of human movement--a statement of the problem. *Med Sci Sports Exerc.* 1985, 17, 304-308.
9. Tartaruga, M.P.; Brisswalter, J.; Peyre-Tartaruga, L.A.; Avila, A.O.; Alberton, C.L.; Coertjens, M.; Cadore, E.L.; Tiggemann, C.L.; Silva, E.M.; Kruel, L.F. The relationship between running economy and biomechanical variables in distance runners. *Res Q Exerc Sport.* 2012, 83, 367-375.

10. Daniels, J.T. A physiologist's view of running economy. *Med Sci Sports Exerc.* 1985, 17, 332-338.
11. Kaneko, M. Mechanics and energetics in running with special reference to efficiency. *J Biomech.* 1990, 23 Suppl 1, 57-63.
12. Winter, D.A. A new definition of mechanical work done in human movement. *J Appl Physiol.* 1979, 46, 79-83.
13. Mayhew, J.L. Oxygen cost and energy expenditure of running in trained runners. *Br J Sports Med.* 1977, 11, 116-121.
14. Cavagna, G.A. Symmetry and asymmetry in bouncing gaits. *Symmetry.* 2010, 2, 1270-1321.
15. Cureton, K.J.; Sparling, P.B.; Evans, B.W.; Johnson, S.M.; Kong, U.D.; Purvis, J.W. Effect of experimental alterations in excess weight on aerobic capacity and distance running performance. *Med Sci Sports.* 1978, 10, 194-199.
16. Cavagna, G.A.; Legramandi, M.A.; Peyre-Tartaruga, L.A. Old men running: mechanical work and elastic bounce. *Proc Biol Sci.* 2008, 275, 411-418.
17. Minetti, A.E.; Capelli, C.; Zamparo, P.; Di Prampero, P.E.; Saibene, F. Effects of stride frequency on mechanical power and energy expenditure of walking. *Med Sci Sports Exerc.* 1995, 27, 1194-1202.
18. Lazzer, S.; Salvadego, D.; Rejc, E.; Buglione, A.; Antonutto, G.; Di Prampero, P.E. The energetics of ultra-endurance running. *Eur J Appl Physiol.* 2012, 112, 1709-1715.
19. Bergh, U.; Sjodin, B.; Forsberg, A.; Svedenhag, J. The relationship between body mass and oxygen uptake during running in humans. *Med Sci Sports Exerc.* 1991, 23, 205-211.
20. Markovic, G.; Vucetic, V.; Nevill, A.M. Scaling behaviour of VO₂ in athletes and untrained individuals. *Ann Hum Biol.* 2007, 34, 315-328.
21. Legramandi, M.A.; Schepens, B.; Cavagna, G.A. Running humans attain optimal elastic bounce in their teens. *Sci Rep.* 2013, 3, 1310.
22. Siri, W.E. Body composition from fluid spaces and density: analysis of methods. 1961. *Nutrition.* 1993, 9, 480-491.
23. Reis, V.M.; Carneiro, A.L.; Methodology to estimate the accumulated oxygen deficit. *Braz J Sci Mov.* 2005, 13, 7-15.
24. Medbo, J.I.; Mohn, A.C.; Tabata, I.; Bahr, R.; Vaage, O.; Sejersted, O.M. Anaerobic capacity determined by maximal accumulated O₂ deficit. *J Appl Physiol.* 1988, 64, 50-60.
25. Barros, R.M.L.; Brenzikofer, R.; Leite, N.J.; Figueroa, P.J. Development and evaluation of a system for three-dimensional kinematic analysis of human movements. *Braz J Biom Eng.* 1999, 15, 79-86.

26. Dempster, W.T.; Gabel, W.C.; Felts, W.J. The anthropometry of the manual work space for the seated subject. *Am J Phys Anthropol.* 1959, 17, 289-317.
27. Minetti, A.E.; Ardigo, L.P.; Saibene, F. Mechanical determinants of gradient walking energetics in man. *J Physiol.* 1993, 472, 725-735.
28. Minetti, A.E.; Ardigo, L.P.; Saibene, F. Mechanical determinants of the minimum energy cost of gradient running in humans. *J Exp Biol.* 1994, 195, 211-225.
29. Mian, O.S.; Thom, J.M.; Ardigo, L.P.; Narici, M.V.; Minetti, A.E. Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiol (Oxf).* 2006, 186, 127-139.
30. Smith, R.J. Allometric scaling in comparative biology: problems of concept and method. *Am J Physiol.* 1984, 246, R152-160.
31. Darveau, C.A.; Suarez, R.K.; Andrews, R.D.; Hochachka, P.W. Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature.* 2002, 417, 166-170.
32. Tartaruga, M.P.; Peyré-Tartaruga, L.A.; Coertjens, M.; Medeiros, M.H.; Kruel, L.F.M. The influence of the allometric scale on the relationship between running economy and biomechanical variables in distance runners. *Biol Sport.* 2009, 26, 263-273.
33. Paterson, D.H.; McLellan, T.M.; Stella, R.S.; Cunningham, D.A. Longitudinal study of ventilation threshold and maximal O₂ uptake in athletic boys. *J Appl Physiol.* 1987, 62, 2051-2057.
34. Weibel, E.R. Physiology: the pitfalls of power laws. *Nature.* 2002, 417, 131-132.
35. Bishop, C.M. The maximum oxygen consumption and aerobic scope of birds and mammals: getting to the heart of the matter. *Proc Biol Sci.* 1999, 266, 2275-2281.
36. Weibel, E.R.; Bacigalupe, L.D.; Schmitt, B.; Hoppeler, H. Allometric scaling of maximal metabolic rate in mammals: muscle aerobic capacity as determinant factor. *Respir Physiol Neurobiol.* 2004, 140, 115-132.
37. Bassett, D.R.; Howley, E.T. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc.* 2000, 32, 70-84.
38. Di Prampero, P.E.; Atchou, G.; Bruckner, J.C.; Moia, C. The energetics of endurance running. *Eur J Appl Physiol.* 1986, 55, 259-266.
39. Foster, C.; Lucia, A. Running economy: the forgotten factor in elite performance. *Sports Med.* 2007, 37, 316-319.
40. Saunders, P.U.; Pyne, D.B.; Telford, R.D.; Hawley, J.A. Factors affecting running economy in trained distance runners. *Sports Med.* 2004, 34, 465-485.
41. Morgan, D.W.; Craib, M. Physiological aspects of running economy. *Med Sci Sports Exerc.* 1992, 24, 456-461.

42. Bailey, S.P.; Pate, R.R. Feasibility of improving running economy. *Sports Med.* 1991, 12, 228-236.
43. Davies, C.T. Metabolic cost of exercise and physical performance in children with some observations on external loading. *Eur J Appl Physiol.* 1980, 45, 95-102.
44. Cooke, C.B.; McDonagh, M.J.; Nevill, A.M.; Davies, C.T. Effects of load on oxygen intake in trained boys and men during treadmill running. *J Appl Physiol.* 1991, 71, 1237-1244.
45. Schepens, B.; Willems, P.A.; Cavagna, G.A.; Heglund, N.C. Mechanical power and efficiency in running children. *Pflugers Arch.* 2001, 442, 107-116.
46. Candau, R.; Belli, A.; Millet, G.Y.; Georges, D.; Barbier, B.; Rouillon, J.D. Energy cost and running mechanics during a treadmill run to voluntary exhaustion in humans. *Eur J Appl Physiol.* 1998, 77, 479-485.
47. Lloyd, B.B.; Zacks, R.M. The mechanical efficiency of treadmill running against a horizontal impeding force. *J Physiol.* 1972, 223, 355-363.
48. Billat, L.V. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. *Sports Med.* 2001, 31, 13-31.
49. Noordhof, D.A.; De Koning, J.J.; Foster, C. The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity? *Sports Med.* 2010, 40, 285-302.
50. Cooper, D.M.; Weiler-Ravell, D.; Whipp, B.J.; Wasserman, K. Aerobic parameters of exercise as a function of body size during growth in children. *J Appl Physiol.* 1984, 56, 628-634.

CONCLUSÃO

A partir dos resultados apresentados nos três estudos originais, conclui-se que a escala alométrica pode melhorar a relação entre ECO e desempenho em meia e longa-distância, principalmente de corredores recreacionistas, devido a influência dos aspectos morfofuncionais no desempenho físico. Da mesma forma, para esta mesma população, os trabalhos mecânicos, especialmente o W_{ext} , podem ser considerados preditores do desempenho, e um expoente alométrico específico pode melhorar essas previsões. Em relação a E_f , os resultados demonstraram que, assim como ocorre com a ECO e com os trabalhos mecânicos, esta também é uma importante variável preditora do desempenho em provas de longa-distância. Entretanto, quando aplicada a alometria, não houve melhora na previsão do desempenho advindo da E_f . Os resultados também demonstraram que para o cálculo da E_f deve-se considerar a contribuição da AnE pois, do contrário, os resultados podem ser superestimados, como já verificados em outros estudos. Em suma, quando o objetivo for prever o desempenho de corredores recreacionistas, meio-fundistas ou fundistas, através das potências metabólica ou mecânica, sugere-se adotar um expoente alométrico específico do grupo investigado. No entanto, quando essa previsão for realizada considerando-se a E_f , especificamente em corredores de alto-rendimento, a aplicação alométrica não é necessária.

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO (TCLE)
Conselho Nacional de Saúde, Resolução 196/96

Eu _____,
portador do documento de identidade número _____ concordo voluntariamente participar do estudo "INFLUÊNCIA ALOMÉTRICA NA ECONOMIA E NA EFICIÊNCIA MECÂNICA DA CORRIDA HUMANA".

Declaro estar ciente de que o estudo a ser desenvolvido tem como objetivo investigar a influência alométrica na predição do desempenho de corredores de longa distância através da ECO e da Ef. Estou ciente de que as informações obtidas no decorrer deste trabalho serão utilizadas para a elaboração da TESE DE DOUTORADO do professor MARCUS PEIKRISZWILI TARTARUGA, sob a responsabilidade do Prof. CARLOS BOLLI MOTA, e que todas as informações utilizadas deverão manter sigilo dos indivíduos avaliados.

- ✓ Compreendo que serei solicitado a:
 - Fazer-me medidas corporais;
 - Fazer-me correr em intensidades máximas e submáximas pré-determinadas;
 - Fazer-me correr em máximo esforço em uma distância de 10.000 metros.
- ✓ Eu entendo que durante os testes:
 - Os procedimentos expostos acima têm sido explicados para mim por Marcus Peikriszwili Tartaruga;
 - Posso sentir dor e cansaço muscular temporário;
 - Posso abandonar os testes e/ou avaliações em qualquer momento sob meu critério;
- ✓ Eu entendo que em qualquer momento o professor Marcus Peikriszwili Tartaruga irá responder qualquer dúvida que eu tenha relativo a estes procedimentos.
- ✓ Eu entendo que todos os dados relativos a minha pessoa irão ficar confidenciais e disponíveis apenas sob minha solicitação escrita. Além disso, eu entendo que no momento da publicação, não irá ser feita associação entre os dados publicados e a minha pessoa.
- ✓ Não há compensação monetária pela minha participação nesse estudo;
- ✓ Eu entendo que não terei gastos monetários para participação na pesquisa, inclusive com o transporte até o local de avaliação;
- ✓ Eu entendo que eventuais danos e riscos da execução da pesquisa serão de responsabilidade do pesquisador;
- ✓ Eu entendo que posso realizar contato com o Prof. Marcus Peikriszwili Tartaruga para quaisquer problemas referentes à minha participação no estudo, ou caso eu sentir que haja violação dos meus direitos, através dos telefones (51) 3308-5817 (LAPEX/UFRGS) ou (42) 9911-3004.

Porto Alegre _____ de _____ de 2012.

Assinatura do avaliado

Prof. Marcus Peikriszwili Tartaruga



Universidade Estadual do Centro-Oeste

Reconhecida pelo Decreto Estadual nº 3.444, de 8 de agosto de 1997

COMITÊ DE ÉTICA EM PESQUISA - COMEP/UNICENTRO/G

Ofício nº 454/2011 - COMEP/UNICENTRO/G


Guarapuava, 31 de Outubro de 2011.

Senhor Professor,

1. Comunicamos que o seu projeto de pesquisa intitulado: "Influência Alométrica na economia e na eficiência mecânica da corrida humana" folha de rosto nº 463742 parecer 211/2011 foi analisado e considerado **APROVADO** pelo Comitê de Ética em Pesquisa de nossa Instituição em Reunião Extraordinária no dia 25 de Outubro de 2011.
2. Em atendimento ao Ofício Circular 017/2011 CONEP/CNS/MS informamos que desde 01/04/2011 é **obrigatória a rubrica em todas as páginas do TCLE** pelo sujeito de pesquisa ou seu responsável e pelos pesquisadores. As referidas assinaturas deverão ser apostas no fim de cada página.
3. Em atendimento à Resolução 196/96 do CNS, deverá ser encaminhado ao COMEP o relatório final da pesquisa e a publicação de seus resultados, para acompanhamento do mesmo.
4. Observamos ainda que se mantenha a devida atenção aos Relatórios Parciais e Finais na seguinte ordem:
 - Os **Relatórios Parciais** deverão ser encaminhados ao COMEP assim que tenha transcorrido um ano da pesquisa.
 - Os **Relatórios Finais** deverão ser encaminhados ao COMEP em até **30 dias após a conclusão da pesquisa**.
5. **Qualquer alteração na pesquisa** que foi aprovada, como por exemplo, números de sujeitos, local, período, etc. deverá ser necessariamente enviada uma carta justificativa para a análise do COMEP.

Pesquisador: Marcus Peikriswili Tartaruga

Atenciosamente,


Prof. Sueli Godoi
Coordenadora do COMEP/UNICENTRO/G
Port. Nº 2.053/2010 – GR/UNICENTRO

Ao Senhor
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ANEXOS

Biomechanics

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The Relationship Between Running Economy and Biomechanical Variables in Distance Runners

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In this study, we analyzed the relationship between running economy (RE) and biomechanical parameters in a group running at the same relative intensity and same absolute velocity. Sixteen homogeneous male long-distance runners performed a test to determine RE at 4.4 m.s⁻¹, corresponding to 11.1% below velocity at the ventilatory threshold. We found significant correlations between RE and biomechanical variables (vertical oscillation of the center of mass, stride frequency, stride length, balance time, relative stride length, range of elbow motion, internal knee, ankle angles at foot strike, and electromyographic activity of the semitendinosus and rectus femoris muscles). In conclusion, changes in running technique can influence RE and lead to improved running performance.

Key words: electromyography, kinematics, locomotion, oxygen uptake

Running economy (RE) is typically defined as the energy required to run submaximally at a given velocity and is determined by measuring steady-state oxygen consumption ($\dot{V}O_2$) and the respiratory exchange ratio. Considering body mass when running at the same velocity, runners with good RE spend less energy and, therefore, less oxygen than runners with poor RE (Saunders, Pyne, Telford, & Hawley, 2004). A number of factors (Saunders,

Pyne, Telford, & Hawley, 2004) and interventions (i.e., training, motor learning, nutrition strategies) appear to influence RE in highly trained or elite runners (Di Prampero, Atchou, Bruckner, & Moia, 1986; Hausswirth & Brisswalter, 2008).

RE performance during long-distance running has been studied extensively, and results suggest it is an important factor in explaining performance in long-distance events (Conley & Krahenbuhl, 1980; Di Prampero et al., 1986; Di Prampero, 1986; Sawyer et al., 2010). In these studies, RE was recorded during a submaximal intensity exercise performed by runners at the same relative intensity (expressed in percent of velocities reached with maximal oxygen uptake [$\dot{V}O_{2max}$] or corresponding to the ventilatory threshold [VT]). However, these relative velocities represent different absolute running velocities and, thus, distinct levels of mechanical demand.

On the other hand, a second approach sought to relate RE changes with biomechanical parameters, such as the temporal or spatial characteristics of the running pattern (Williams & Cavanagh, 1987), ground reaction force (Nummela, Keranen, & Mikkelsen, 2007; Nummela, Rusko, & Mero, 1994), capacity to store and return elastic energy (Gleim, Stachenfeld, & Nicholas, 1990), or total mechanical work (Mian, Thom, Ardigo, Narici, & Minetti, 2006; Minetti, Ardigo, & Saibene, 1994). In all these studies, RE was recorded for all runners at the same

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absolute running velocity, although it would correspond to different physiological intensities and, thus, distinct levels of metabolic demand. Although several studies analyzed the relationship between RE and biomechanical parameters, the results were contradictory, and few studies found a significant relationship between the kinematic variables, muscle activity in the lower limbs, and RE in long-distance runners (Cavanagh, Pollock, & Landa, 1977; Cavanagh & Williams, 1982; Kyrolainen, Belli, & Komi, 2001).

By analyzing the relationship between RE and the mechanical and neuromuscular variables in participants running at the same velocity, as well as the increased electromyographic signal (EMG) of the working muscles and associated increase in power output, it may be possible to partly explain the variation in energy expenditure (Kyrolainen et al., 2001) that may account for up to 30% of performance in distance runners (Conley & Krahenbuhl, 1980; Saunders, Pyne, Telford, & Hawley, 2004). The increased fractional use of $\dot{V}O_2$ max is immediately accompanied by an increase in amplitude of the electromyographic signal; therefore, the different relative intensities may account for this relationship.

Analyzing within-participant effects, Cavanagh and Williams (1982) found submaximal oxygen uptake ($\dot{V}O_{2\text{submax}}$) increased curvilinearly as stride length either lengthened or shortened from what the runner self-selected. They concluded there is little need to dictate stride length for well trained athletes, as they display near optimal stride length. However, when analyzed between participants, velocity directly influences kinematic parameters. For instance, Cavanagh et al. (1977) found that elite runners showed less vertical oscillation, were more symmetrical, and had better RE. On the other hand, Kyrolainen et al. (2000) reported that some biomechanical parameters (angular velocities and ankle, knee, and hip joint displacements) were not good predictors of RE. Again, athletes performed the tests at the same speeds but at different physiological intensities. Therefore, to achieve a better understanding of the variables involved in long-distance running performance, we analyzed the relationship between RE and biomechanical variables in experienced distance runners, who ran at the same absolute velocity with similar physiological intensity.

Method

Participants

The study sample comprised 16 healthy male volunteers. All were long-distance runners and members of the Athletic Federation of Rio Grande do Sul–Brazil, with times between 30 and 36 min achieved in national competitions (10,000 m) 2–5 weeks prior to the evaluation period, with similar speeds at the VT (verified in an incremental treadmill running protocol), and who were

free of nutritional restrictions. Participant characteristics were (M age = 27 years, SD = 5.7; M body mass = 64.5 kg, SD = 5.8; M height = 1.74 m, SD = 0.08; M leg length = 0.82 m, SD = 0.04; M body density = 1.08 g.ml⁻¹, SD = 0.01; M body fat = 9.11%, SD = 1.48; M training volume = 66.8 km.week⁻¹, SD = 13.6; M experience = 7.7 years, SD = 3.2; and MVO_2 max in treadmill running = 56.36 ml.kg⁻¹.min⁻¹, SD = 4.7). Prior to giving their written consent to participate, all participants were fully informed of the purpose, nature, practical details, and possible risks associated with the experiment, as well as their right to terminate participation at will. The institution's Research Ethics Committee approved the present study according to the Declaration of Helsinki.

Experimental Design

Participants took part in two experimental sessions (see Figure 1) at 2-week intervals. They wore their own spikeless training shoes. The ambient temperature (25°C) and relative humidity (53%) were controlled according to ISO-8573-1 (International Standards).

Preliminary Test. First, anthropometric parameters were recorded (body mass, height, and leg length), using scales and a stadiometer (FILIZOLA, São Paulo, Brazil). The percentage of body fat was calculated using the Siri equation (1993). Body density was calculated using the Jackson and Pollock equation (1978). All athletes performed a treadmill running familiarization session with specific ergospirometric accessories.

Incremental Treadmill Running Protocol. After a brief warm-up and 10-min rest (5 min sitting and 5 min standing), participants performed a progressive protocol with an initial velocity of 2.7 m.s⁻¹, in which speed was increased by 0.27 m.s⁻¹ at 1-min intervals and treadmill incline was fixed at 1% (Peyré-Tartaruga et al., 2009). Load increments were calculated to reach $\dot{V}O_2$ max at between 8 and 14 min. The $\dot{V}O_2$ max attainment criteria described by Howley, Bassett, and Welch (1995) were adopted. Respiratory parameters were continuously recorded using a portable ergospirometer (AEROSPORT-KB1-C, Ann Arbor, MI), with a sampling rate of 20 s. The gas analyzer was calibrated prior to each collection session according to the manufacturer's specifications (King, McLaughlin, Howley, Bassett, & Ainsworth, 1999).

To determine VT, ventilatory equivalents ($VE/\dot{V}O_2$ and VE/VCO_2) for each participant were plotted over the corresponding $\dot{V}O_2$ values. Three independent reviewers assessed VT graphs (Foster & Lucia, 2007; Powers, Dodd, Deason, Byrd, & Mcknight, 1983; Solberg, Robstad, & Skjonsberg, 2005).

Running Economy Determination Test. The RE test (in ml.kg⁻¹.min⁻¹) consisted of a 6-min run at 4.4 m.s⁻¹, on a treadmill (MOVEMENT-RT250, São Paulo, Brazil). This velocity corresponded to a physiological intensity of 89%

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of the average velocity at VT ($5 \text{ m}\cdot\text{s}^{-1}$), corresponding to a predominantly aerobic intensity for all participants. Individual RE was determined based on the mean $\text{VO}_{2\text{submax}}$ values recorded during the last 2 min of the test. As in the incremental treadmill running protocol, the gas analyzer was calibrated prior to each collection session.

Electromyographic Recordings

Maximal activation of the rectus femoris (RF), vastus lateralis (VL), semitendinosus (ST), and short head of the biceps femoris (BF) muscles was determined for later normalization of the EMG signal obtained in the support and balance phases (%MVC), by performing a maximal voluntary contraction (MVC) test. These tests were conducted on land before and after the exercise protocol and consisted of a 5-s contraction of the muscle groups, in which each of the muscles mentioned acted as an agonist. Pretest MVC values were used for further normalization of the EMG signal (Knutson, Soderberg, Ballantyne, & Clarke, 1994).

The angles with highest torque production, measured with a goniometer (CARCI; São Paulo, Brazil), were identified based on the force-length relation (Fenn & Marsh,

1935) and adjusted so that they could be maintained during MVC performance against manual resistance in both flexion and extension directions. In addition, these angles were within the range of motion performed during the protocol. For the RF and ST muscles, the EMG signal was recorded as participants lay face-up with 90° of hip flexion. For the RF, the knee maintained 90° of flexion, with isometric contraction of the hip flexors. For the ST muscle, the knee maintained full extension (0°), with isometric contraction of the hip extensors. Afterward, participants were seated, with 90° of hip and 70° of knee flexion to record the EMG signal from the VL and BF muscles.

Pairs of Ag/AgCl pregelled surface electrodes (radius = 10 mm; TYCO HEALTHCARE, Hampshire, England) were applied after the innervation zone had been determined by using an EGF 4030 electric stimulator (CARCI, São Paulo, Brazil; Dainty & Norman, 1987). The electrode centers were placed 30 mm apart. Before each session, a digital multimeter was used to measure the interelectrode resistance level, which is considered suitable below 3,000 ohms. The reference electrode was positioned on the clavicle, and bipolar electrodes were placed 2 cm distal from the innervation zone.

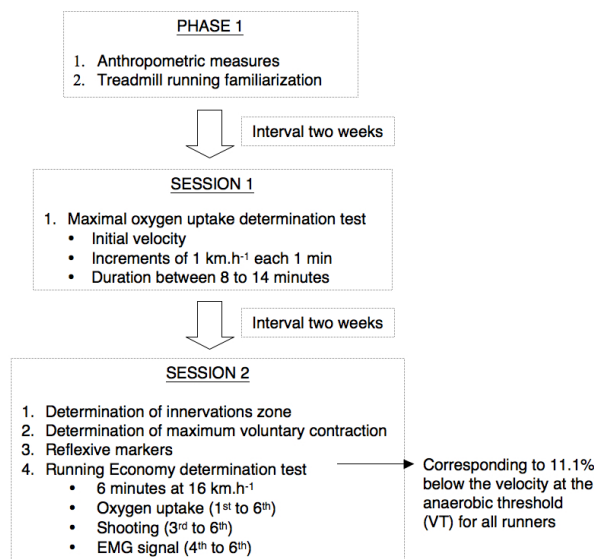


Figure 1. Experimental protocol.

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The EMG signals from the RF, VL, ST, and BF in the support and balance phases were recorded during the last 2 min of the run, using a portable electromyograph (MIOTEC, Porto Alegre, Brazil) with four channels (2000 Hz per channel) and a common rejection mode greater than 126 dB. The data were treated in SAD32 software (Mechanical Measurements Laboratory, UFRGS; Porto Alegre, Brazil). First, signal gains in the raw files were removed. Then the signal was digitally filtered using fifth-order band-pass Butterworth filters with a cut-off frequency between 20 and 450 Hz.

Visual inspection determined participant's foot strike and take-off events in three stride cycles, following the third stride after the fourth minute. Root mean square values (RMS) were obtained for the support and balance phases. The RMS value is used to quantify the EMG signal (Krogh-Lund & Jorgensen, 1991).

Kinematic Analysis

We adopted use of 13 reflective markers, 9 on the left sagittal plane (ear, shoulder, elbow, wrist, hip, knee, ankle, heel, and finger) and 4 in the posterior frontal plane of the left leg (2 points on the heel and ankle, 1 point placed one third from the distal portion of the gastrocnemius muscle, and 1 point where the gastrocnemius muscle originates, as described by Peyré-Tartaruga et al., 2009). During the RE test, kinematic variables (stride time, support time, balance time, stride length, relative stride length, stride frequency, internal knee and ankle angles at foot strike and take-off, maximum trunk flexion and maximum knee flexion in the support phase, range of elbow motion during the stride, maximal pronation of the subtalar joint, and vertical oscillation of the center of mass and external mechanical work) were recorded by two digital cameras (sagittal and posterior frontal planes, 120 Hz; Pulnix Progressive Scan, San Diego, CA). Magnitudes of the kinematic variables were recorded during the last 2 min of the run. The support and balance phases were visually identified during three stride cycles. The center of mass was calculated from the relative position of the body segments (Willems, Cavagna, & Heglund, 1995).

Recordings of the posterior frontal and left sagittal planes were digitized using DVIDEO software (Laboratory of Biomechanics & Institute of Computing, UNICAMP, São Paulo, Brazil). Running technique variables were calculated using three routines developed in MATLAB software, in which a Butterworth filter (fifth order), with a cut-off frequency of 5 Hz, was applied (Winter, 1990). The external mechanical work was also determined using the method from Willems, Cavagna, and Heglund (1995).

Statistical Analysis

Descriptive statistic calculations are presented as means and standard deviations. Normality of the data was

assessed using the Shapiro-Wilk's test. We used Pearson's product-moment correlations to analyze the relationship between RE and the kinematic or muscular variables. For variables that presented significant values of $\alpha < .25$, we performed a multiple linear regression analysis to determine the influence of each independent variable on RE. Hosmer and Lemeshow (2000) recommended the significance level for this type of analysis.

Results

There were significant correlations between RE ($M = 44.85 \text{ ml.kg}^{-1}.\text{min}^{-1}$, $SD = 4.7$) and performance variables (time at 10,000 m: $M = 1,994 \text{ s}$, $SD = 150$; $M\dot{V}O_{2\text{max}} = 56.54 \text{ ml.kg}^{-1}.\text{min}^{-1}$, $SD = 4.7$; $M\dot{V}O_{2\text{VT}} = 49.60 \text{ ml.kg}^{-1}.\text{min}^{-1}$, $SD = 5.4$), demonstrating that RE can predict performance in long-distance running (see Figures 2, 3, and 4). The highest correlation was between RE and performance, because the variability of time at 10,000 m was lower ($SD = 7.5\%$ of average) compared to $\dot{V}O_{2\text{max}}$ (8.3%) and $\dot{V}O_{2\text{VT}}$ (10.8%). Mean velocity at $\dot{V}O_{2\text{max}}$ was 5.93 m.s^{-1} ($SD = 0.3$), and mean velocity at VT was 5.01 m.s^{-1} ($SD = 0.3$).

There were significant correlations between RE and some kinematic variables (vertical oscillation of the center of mass: $r = .65$; stride frequency: $r = -.61$; stride length: $r = .61$; balance time: $r = .61$; relative stride length: $r = .46$; range of elbow motion: $r = .42$; internal knee angle at foot strike: $r = -.41$; and internal ankle angle at foot strike: $r = -.32$) and between RE and muscular variables (RMS of the ST, $r = .59$, and RMS of the RF, $r = -.36$, at balance; and RMS of the ST at support, $r = .34$; see Table 1). In this study, 44.4% of kinematic variables and 66.6% of muscular variables showed a significant correlation with RE.

When using multiple regression analysis, 81% of the kinematic variables and 19% of the muscular variables were included in the RE prediction model. The overall predictive power of the multiple linear regression analysis model was 85.5%, with an estimated error of 2.52. The variables, stride frequency, stride length, internal knee angle at foot strike, percentage of maximum voluntary contractions of the ST muscle (%MVC ST) at support, vertical oscillation of the center of mass, and range of elbow motion showed the highest relationship with RE (see Table 2).

Discussion

We designed the present study to investigate the relationships between several biomechanical parameters and RE in endurance athletes. Running involves the conversion of muscular forces translocated through complex movement patterns that use all major muscles and joints

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in the body. Skill and precise timing are required for high performance running in which all movements have purpose and function (Anderson, 1996). Clearly, changing aspects of running mechanics that result in a runner using less energy at any given speed is advantageous to performance (Cavanagh & Williams, 1982).

Several relationships between biomechanical parameters and RE have been studied. The most frequently analyzed has been the relationship between stride length and/or stride frequency and RE (Nummela et al., 1994; Nummela et al., 2007; Williams & Cavanagh, 1987). In our study, stride frequency and length showed significant relationships with RE ($r = -.61$ and $r = .61$, respectively). According to the multiple regression analysis, these variables correspond to 28% and 23%, respectively, of the overall influence of biomechanical parameters on RE.

Cavanagh and Williams (1982) and Nummela et al. (2007) reported that the relatively efficient patterns used during running indicate either an adaptation to the chosen stride length through training (biomechanical adaptation) or a successful process of energy optimization (physiological adaptation). These adaptations result in a negative relationship between stride frequency and RE and a positive relationship between stride length and RE. Moreover, Bailey and Pate (1991), Saunders et al. (2004),

Dallam, Wilber, Jadelis, Fletcher, and Romanov (2005), and Chen, Nosaka, Lin, Chen, and Wu (2009) showed that elite male distance runners had a better combination of stride frequency and length compared with good male distance runners and, consequently, a better RE. The strong correlations of stride frequency and length with RE and better combinations between stride frequency and stride length seen in our sample was probably due to their considerable professional experience, which corroborates findings in the literature.

Many studies have demonstrated that support and balance times are key factors affecting running energetics and mechanics (Morin, Samozino, Zameziati, & Belli, 2007). In their investigation of the relationships between support time, step frequency, and leg stiffness in human running, Morin et al. (2007) showed that support time, associated with balance time, could be a major determinant of this spring-mass characteristic of human running. Similarly, Clarke (1991) indicated that, during locomotion, the running technique is adjusted by changes to stride length and stride time, variables influenced by support and balance times. In our study, balance time presented a significant correlation ($r = .61$) and a predictive power of 3.2% with the RE. This correlation probably influenced the relationship between stride length and RE

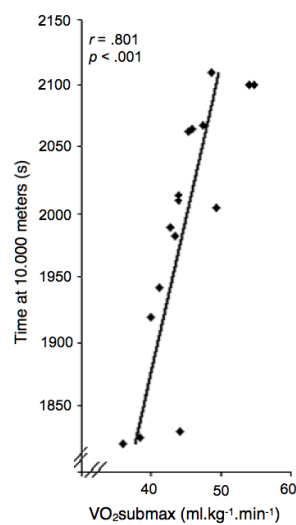


Figure 2. Correlation between submaximal oxygen consumption ($VO_{2submax}$) and performance.

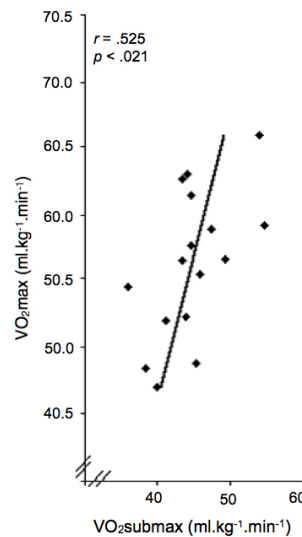


Figure 3. Correlation between submaximal oxygen consumption ($VO_{2submax}$) and maximal oxygen consumption (VO_{2max}).

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in our runners. The increase in balance time may result in decreased stride frequency, increased stride length, and, consequently, increased RE, as suggested by our results.

The mechanical work performed during exercise has often been studied in relation with RE. For this purpose, different models, such as the center of mass, segment-based, or kinetic models, have been used (Martin, Heise, & Morgan, 1993). In the center of mass model, vertical oscillation of the center of mass can be used to reflect the mechanical work. For example, Cavanagh et al. (1977) found that elite runners showed less vertical oscillation, were more symmetrical, and had better RE. However, Williams and Cavanagh (1987) analyzed the relationship between running mechanics, RE, and performance in 31 participants running at 3.6 m.s⁻¹ and reported that those with the best RE had greater vertical oscillation of the center of mass. Cavagna, Heglund, and Willems (2005) reported that less vertical oscillation results in: (a) higher stride frequency, (b) lower variation of external energy, and (c) higher internal work to accelerate segments within the center of mass, thus, increasing the metabolic cost of running. Our results are in agreement with this hypothesis, and there was a significant correlation ($r = .65$) between vertical oscillation of the center of mass and RE,

as well as 7.2% predictive power, indicating that greater vertical oscillation is linked to a decrease in metabolic demand. We found significant correlations between internal knee and internal ankle angles, both at foot strike and RE ($r = -.41$ and $r = -.32$). These parameters predict 12.7% and 0.6% of RE in the multiple model, respectively. These findings corroborate those of Kyrolainen et al. (2001) and Gollhofer, Komi, Miyashita, and Aura (1987), who reported that greater muscular-tendon rigidity and lower degree of joint absorbcency during athletic walking result in greater energy spent during treadmill running.

One interesting result of our study using kinematics analysis is the positive relationship between the range of

Table 1. Pearson product-moment correlations between running economy and biomechanical variables

Biomechanical variables	M	SD	r	p
Stride time (s)	0.69	0.04	.608	.012*
Support time (s)	0.21	0.01	.058	.832
Balance time (s)	0.48	0.03	.613	.012*
Stride length (m)	3.07	0.16	.608	.013*
Relative stride length (m)	3.74	0.24	.461	.072*
Stride frequency (pass/s)	1.45	0.08	-.613	.012*
Internal knee angle at foot strike (°)	159.26	6.12	-.409	.115*
Internal knee angle at take-off (°)	156.71	4.04	-.006	.984
Internal ankle angle at foot strike (°)	121.99	6.64	-.318	.230*
Internal ankle angle at take-off (°)	138.98	8.16	-.030	.913
Maximum knee flexion in the support phase (°)	128.12	12.32	-.239	.372
Maximum trunk flexion in the support phase (°)	14.86	4.32	.182	.500
Range of elbow motion (°)	38.84	12.60	.418	.107*
Maximal pronation of the subtalar joint (°)	11.69	4.56	.122	.653
Vertical oscillation of the center of mass (m)	9.52	1.00	.651	.006*
External mechanical work (J)	0.99	0.08	-.346	.289
%MVC RF at support	13.44	3.54	-.086	.750
%MVC VL at support	14.08	5.28	-.068	.802
%MVC ST at support	27.14	4.98	-.340	.198*
%MVC BF at support	19.89	3.63	.095	.726
%MVC RF at balance	14.38	1.99	-.364	.166*
%MVC VL at balance	39.36	4.47	.037	.893
%MVC ST at balance	34.31	4.33	.593	.015*
%MVC BF at balance	30.14	4.35	.014	.959
EMG total (Mv)	1247.70	76.00	.340	.298

Note. M = mean; SD = standard deviation; %MVC = percentage of maximum voluntary contractions; RF = rectus femoris; VL = vastus lateralis; ST = semitendinosus muscle; BF = biceps femoris; and EMG = electromyographic.
*Variables with $\alpha < .25$.

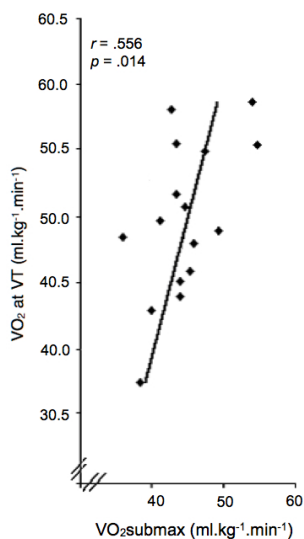


Figure 4. Correlation between submaximal oxygen consumption ($VO_{2submax}$) and VO_2 at ventilatory threshold (VT).

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elbow motion during stride and RE ($r = .42$). Furthermore, we found a significant relationship ($r = .54$) between the range of elbow motion and stride length, indicating that, in part, participants with a shorter stride have a shorter arm movement. Arm movement is an important factor contributing to reducing oscillations in the transverse plane (Umberger, 2008) and increasing equilibrium of lower limb angular momentum over the body's vertical axis (Hinrichs, 1987) while running, resulting in enhanced global body equilibrium. Within this context, it has been observed that participants who use a short range of motion in the shoulder and elbow joints when running tend to have greater postural disequilibrium and, consequently lower RE (Tartaruga, Tartaruga, Ribeiro, Coertjens, Ribas, & Krueel, 2004).

Analysis of surface EMG activity has been used to study running technique (Hauswirth, Brisswalter, Vallier, Smith, & Lepers, 2000). When investigating kinematics, kinetics, and muscle activity in relation to RE at different running speeds, Kyrolainen et al. (2001) found significant correlations (range: $r = .45$ – $.48$) between RE and muscular electrical activation, suggesting a positive relationship in runners with good running technique. However, Hauswirth, Bigard, and Guezennec (1997), compared the EMG signal of the VL muscle in 7 participants during the running section of a triathlon and at the end of a prolonged run performed at the same running velocity. They found greater values for $\text{VO}_{2\text{submax}}$, RMS, and heart rate during the prolonged run compared to the triathlon run, suggesting a negative relationship between RE and muscular electrical activation. The contrasting findings reported in

these studies may be related to different motor activation patterns and, consequently, different running techniques.

In our study, the EMG values had an overall predictive power of 19.1% in relation to RE. There were significant correlations between RE and RMS values of the ST in the support (11.3% for $r = .34$) and balance (3.4% for $r = .59$) phases and between RE and RMS values of the RF in the balance phase (4.3% for $r = -.36$).

The ST is a biarticular muscle activated during hip extension and knee flexion. It allows the gluteus maximus, in the support phase, and the semimembranosus and BF muscles, in the balance phase, to diminish electrical muscular activation during the stride, consequently increasing RE (Thompson & Floyd, 1998). Furthermore, specific training to improve the neural component (motor unit recruitment patterns and augmentation in action potential conduction velocity over the muscle), to obtain greater efficiency from the ST muscle could also contribute to increasing RE and, thus, enhanced performance.

Besides acting as a knee extensor at the end of the balance phase, the RF acts as a powerful hip flexor, mainly during the contact phase, leading the center of mass to be projected forward (Montgomery, Pink, & Perry, 1994; Thompson & Floyd, 1998). Nevertheless, its action is considered auxiliary, due to the action of the iliopsoas muscle, mainly during knee extension at the end of the balance phase. Its contribution to knee extension is probably greater in relation to the hip flexion, making its relationship with the RE significant in the balance phase.

We found no significant relationship between the BF and VL muscles and RE. It is possible the ST actions during the support and balance phases and the RF in the balance phase are the main actions that influence RE, reducing the BF and VL actions (monoarticular muscles) in the support and balance phases. This may occur because the RF, according Montgomery et al. (1994) and Thompson and Floyd (1997), acts by eccentrically assisting the iliopsoas muscle during the support phase, decreasing the relationship with RE.

Conclusion

Our study showed changes in running technique and muscle activity related with RE in experienced 10,000-m runners at intensities below VT. While training for long-distance running, reduction in stride frequency and increase in stride length may enhance performance due to the increased RE. We identified exclusive biomechanical parameters to explain RE. This has important implications that should be considered when coaches or athletes make alterations to running technique.

References

Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine*, 22, 76–89.

Table 2. Results of the multiple linear regression analysis

Biomechanical variables	Adjusted coefficients	Relationship (%)
Stride frequency	2.275	28.3
Stride length	1.848	23.0
Internal knee angle at foot strike	1.022	12.7
%MVC ST at support	0.911	11.3
Vertical oscillation of the center of mass	0.580	7.2
Range of elbow motion	0.447	5.6
%MVC RF at balance	0.346	4.3
%MVC ST at balance	0.276	3.4
Balance time	0.252	3.2
Internal ankle angle at foot strike	0.049	0.6
Relative stride length	0.021	0.4
Total		100.0

Note: %MVC = percentage of maximum voluntary contractions; ST = semitendinosus muscle; RF = rectus femoris muscle; variable related: oxygen uptake at 4.4 m.s⁻¹; variable excluded by the regression model: stride time ($\alpha > .05$).

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- Bailey, S. P., & Pate, R. R. (1991). Feasibility of improving running economy. *Sports Medicine*, 12, 228–236.
- Cavagna, G. A., Heglund, N. C., & Willems, P. A. (2005). Effect of an increase in gravity on the power output and the rebound of the body in human running. *Journal of Experimental Biology*, 208, 2333–2346.
- Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine & Science in Sports & Exercise*, 14, 30–35.
- Cavanagh, P. R., Pollock, M. L., & Landa, J. (1977). A biomechanical comparison of elite and good distance runners. *Annals of the New York Academy of Sciences*, 301, 328–345.
- Chen, T. C., Nosaka, K., Lin, M. J., Chen, H. L., & Wu, C. J. (2009). Changes in running economy at different intensities following downhill running. *Journal of Sports Sciences*, 27, 1137–1144.
- Clarke, K. A. (1991). Swing time changes contribute to stride time adjustment in the walking rat. *Physiology and Behavior*, 50, 1261–1262.
- Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. *Medicine & Science in Sports & Exercise*, 12, 357–360.
- Dainty, D. A., & Norman, R. W. (1987). *Standardizing biomechanical testing in sport*. Champaign, IL: Human Kinetics.
- Dallam, G. M., Wilber, R. L., Jadelis, K., Fletcher, G., & Romanov, N. (2005). Effect of a global alteration of running technique on kinematics and economy. *Journal of Sports Sciences*, 23, 757–764.
- Di Prampero, P. E. (1986). The energy cost of human locomotion on land and in water. *International Journal of Sports Medicine*, 7, 55–72.
- Di Prampero, P. E., Atchou, G., Bruckner, J. C., & Moia, C. (1986). The energetics of endurance running. *European Journal of Applied Physiology and Occupational Physiology*, 55, 259–266.
- Fenn, W. O., & Marsh, B. S. (1935). Muscular force at different speeds of shortening. *Journal of Physiology*, 85, 277–297.
- Foster, C., & Lucia, A. (2007). Running economy: The forgotten factor in elite performance. *Sports Medicine*, 37, 316–319.
- Gleim, G. W., Stachenfeld, N. S., & Nicholas, J. A. (1990). The influence of flexibility on the economy of walking and jogging. *Journal of Orthopaedic Research*, 8, 814–823.
- Gollhofer, A., Komi, P. V., Miyashita, M., & Aura, O. (1987). Fatigue during stretch-shortening cycle exercises: Changes in mechanical performance of human skeletal muscle. *International Journal of Sports Medicine*, 8, 71–78.
- Hauswirth, C., & Brisswalter, J. (2008). Strategies for improving performance in long duration events: Olympic distance triathlon. *Sports Medicine*, 38, 881–891.
- Hauswirth, C., Bigard, A. X., & Guezennec, C. Y. (1997). Relationships between running mechanics and energy cost of running at the end of a triathlon and a marathon. *International Journal of Sports Medicine*, 18, 330–339.
- Hauswirth, C., Brisswalter, J., Vallier, J. M., Smith, D., & Lepers, R. (2000). Evolution of electromyographic signal, running economy, and perceived exertion during different prolonged exercises. *International Journal of Sports Medicine*, 21, 429–436.
- Hinrichs, R. (1987). Upper extremity function in running. II. Angular momentum considerations. *International Journal of Sport Biomechanics*, 3, 242–263.
- Hosmer, D. W., & Lemeshow, S. (2000). *Applied logistic regression*. New York: Wiley.
- Howley, E. T., Bassett, D. R., Jr., & Welch, H. G. (1995). Criteria for maximal oxygen uptake: Review and commentary. *Medicine & Science in Sports & Exercise*, 27, 1292–1301.
- Jackson, A. S., & Pollock, M. L. (1978). Generalized equation for predicting body density of men. *British Journal of Nutrition*, 40, 497–504.
- King, G. A., McLaughlin, J. E., Howley, E. T., Bassett D. R., Jr., & Ainsworth, B. E. (1999). Validation of Aerosport KB1-C portable metabolic system. *International Journal of Sports Medicine*, 20, 304–308.
- Knutson, L. M., Soderberg, G. L., Ballantyne, B. T., & Clarke, W. R. (1994). A study of various normalization procedures for within day electromyographic data. *Journal of Electromyography and Kinesiology*, 4, 47–59.
- Krogh-Lund, C., & Jorgensen, K. (1991). Changes in conduction velocity, median frequency, and root mean square-amplitude of the electromyogram during 25% maximal voluntary contraction of the triceps brachii muscle, to limit of endurance. *European Journal of Applied Physiology and Occupational Physiology*, 63, 60–69.
- Kyrolainen, H., Belli, A., & Komi, P. V. (2001). Biomechanical factors affecting running economy. *Medicine & Science in Sports & Exercise*, 33, 1330–1337.
- Martin, P. E., Heise, G. D., & Morgan, D. W. (1993). Interrelationships between mechanical power, energy transfers, and walking and running economy. *Medicine & Science in Sports & Exercise*, 25, 508–515.
- Mian, O. S., Thom, J. M., Ardigo, L. P., Narici, M. V., & Minetti, A. E. (2006). Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiologica*, 186, 127–139.
- Minetti, A. E., Ardigo, L. P., & Saibene, F. (1994). Mechanical determinants of the minimum energy cost of gradient running in humans. *Journal of Experimental Biology*, 195, 211–225.
- Montgomery, W. H., Pink, M., & Perry, J. (1994). Electromyographic analysis of hip and knee musculature during running. *The American Journal of Sports Medicine*, 22, 272–278.
- Morin, J. B., Samozino, P., Zameziati, K., & Belli, A. (2007). Effects of altered stride frequency and contact time on leg-spring behavior in human running. *Journal of Biomechanics*, 40, 3341–3348.
- Nummela, A., Keranen, T., & Mikkelsen, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine*, 28, 655–661.
- Nummela, A., Rusko, H., & Mero, A. (1994). EMG activities and ground reaction forces during fatigued and nonfatigued sprinting. *Medicine & Science in Sports & Exercise*, 26, 605–609.
- Peyré-Tartaruga, L. A., Tartaruga, M. P., Coertjens, M., Black, G. L., Oliveira, A. R., & Kruei, L. F. M. (2009). Physiologic and kinematic effects of water run training on running performance. *International Journal of Aquatic Research and Education*, 3, 135–150.
- Powers, S. K., Dodd, S., Deason, R., Byrd, R., & Mcknight, T. (1983). Ventilatory threshold, running economy and dis-

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- tance running performance of trained athletes. *Research Quarterly for Exercise and Sport*, 54, 179–182.
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34, 465–485.
- Sawyer, B. J., Blessinger, J. R., Irving, B. A., Weltman, A., Patrie, J. T., & Gaesser, G. A. (2010). Walking and running economy: Inverse association with peak oxygen uptake. *Medicine & Science in Sports & Exercise*, 42, 2122–2127.
- Siri, W. E. (1993). Body composition from fluid spaces and density: Analysis of methods. *Nutrition*, 9, 480–491.
- Solberg, G., Robstad, B., Skjonsberg, O. H., & Borchsenius, F. (2005). Respiratory gas exchange indices for estimating the anaerobic threshold. *Journal of Sports Science and Medicine*, 4, 29–36.
- Tartaruga, L. A. P., Tartaruga, M. P., Ribeiro, J. L., Coertjens, M., Ribas, L. R., & Krue, L. F. M. (2004). Correlation between running economy and kinematic variables in high level runners. *Brazilian Journal of Biomechanics*, 5, 51–58.
- Thompson, F. W., & Floyd, R. T. (1998). *Manual of structural kinesiology*. St. Louis, MO: Mosby.
- Umberger, B. R. (2008). Effects of suppressing arm swing on kinematics, kinetics, and energetics of human walking. *Journal of Biomechanics*, 41, 2575–2580.
- Willems, P. A., Cavagna, G. A., & Heglund, N. C. (1995). External, internal and total work in human locomotion. *Journal of Experimental Biology*, 198, 379–393.
- Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, 63, 1236–1245.
- Winter, D. A. (1990). Processing of raw kinematic data. In D. A. Winter (Ed.), *Biomechanics of human movement* (pp. 24–39). New York: John Wiley.

Authors' Notes

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APPLICATION OF THE ALLOMETRIC SCALE FOR THE SUBMAXIMAL OXYGEN UPTAKE IN RUNNERS AND ROWERS

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ABSTRACT: Background: The aim of the current study was to determine the allometric exponents for runners and rower's metabolic cost, while also verifying the relation of performance with and without the allometric application. Methods: Eleven runners (age: 22.3 ± 10.4 years; height: 174 ± 8.8 cm; body mass: 61.7 ± 9.3 kg; maximum oxygen uptake ($\dot{V}O_{2\max}$): 56.3 ± 3.9 ml kg⁻¹ min⁻¹) and fifteen rowers (age: 24 ± 5.4 years; height: 185.5 ± 6.5 cm; body mass: 83.5 ± 7.2 kg; $\dot{V}O_{2\max}$: 61.2 ± 3.4 ml kg⁻¹ min⁻¹) carried out a specific progressive maximum test. The allometric exponent was determined from the logarithmic equation $\text{Log } y = \text{Log } a + b \text{ Log } x$, where x is the mass, y is the $\dot{V}O_{2\max}$ (l min⁻¹), a is one constant and b is the allometric exponent. The data were analyzed using descriptive and comparative statistics (independent T test of the Student), with $p < 0.05$ (SPSS version 13.0). Results: The allometric exponent of the rowers was 0.70 and that of the runners was 1.00. Significant differences were found between the fat mass percentage, with higher value for rowers, suggesting that this variable may influence the behavior of the allometric exponent and consequently of the basal metabolic rate. Conclusions: Scaling may help in understanding variation in aerobic power and in defining the physiological limitations of work capacity.

KEY WORDS: biomechanics, physiology, exercise physiology, running, rowing

INTRODUCTION

An organism with a larger body mass has a higher metabolic rate than an organism with a smaller body mass because there is a proportional relationship between mass and metabolism [7]. However, larger organisms may present lower physiological values than smaller organisms when the values of this variable are normalized by body mass values [11,13]. In the first case, the metabolic rate is expressed in absolute terms by a unit that represents the total amount of the evaluated variable. In the second case, it is expressed in relative terms by a unit that represents the amount of the evaluated variable for each kilogram of body mass.

The maximum oxygen uptake ($\dot{V}O_{2\max}$) is considered the main measure for evaluating cardiorespiratory conditioning. It can be expressed in absolute terms (l min⁻¹) or relative to the body weight (ml kg⁻¹ min⁻¹) [14]. The relative values are used to make comparisons between subjects that differ in terms of body mass and lean body mass, height and percentage of fat, since the muscle involved in the activity influences these values [6]. However, in high performance sports, the submaximal oxygen uptake ($\dot{V}O_{2\text{submax}}$), that is the economy of movement, has been shown to be better parameter

when assessing performance. The $\dot{V}O_{2\text{submax}}$ or economy running, defined as the oxygen uptake at a determined submaximal intensity of movement, can be responsible for up to 30% of the performance in long distance runners [4].

Brisswalter *et al.* [2], West *et al.* [18] and Darveau *et al.* [5] point out the need to use parameters that allow comparison of physiological variables, such as the $\dot{V}O_{2\max}$, between individuals with different masses. An example is the allometric scale [11,13,19]. It is represented by means of an equation that indicates the behaviour of a physiological variable Y in relation to the variable mass X ($Y = aX^b$), where a is the allometric coefficient (a constant that is characteristic for the organism) and b is the allometric or scaling exponent. This exponential function can be transformed into a linear function: $\text{Log } y = \text{Log } a + b \text{ Log } x$.

In relation to the practice of sports, studies have reported the need to use different values, such as allometric coefficients, in order to determine the percentage of total body mass to be considered. These values would be specific for different sports [11], as well as for wheelchair users [8]. Regarding this, Saltin and Astrand [15]

affirm that the relationship between $\dot{V}O_2\text{max}$ and body mass is used because there are many types of locomotion and each one requires a body mass to be moved.

In their analysis of the relationship between $\dot{V}O_2\text{max}$ and body mass in 967 athletes, representing 25 different sports, Jensen *et al.* [11] found different values for b in each type of sport analyzed. Later, an approximate mean exponent of 0.73 was calculated for all modalities, which permitted the creation of a ranking of aerobic capacity headed by long-distance cyclists and runners.

Assuming that the allometric scale allows a different analysis of the results, there arises the need to analyze the performance of athletes from two distinct types of modality: running and rowing. Considering the specific characteristics of each modality and the body composition of the athletes, the purpose of this study was to determine the allometric exponents for runners and rowers, while analyzing the relationship to performance with and without the use of allometrics.

MATERIALS AND METHODS

Eleven male long-distance runners and fifteen male elite rowers volunteered and were selected for the study. In accordance with the recommendations of the American College of Sports Medicine (ACSM) [1], all the subjects filled out forms with their personal details and read and signed an informed consent form approved by the Research Ethics Committee of the Federal University of Rio Grande do Sul, Brazil. The characteristics of the sample are presented in Table 1. All the athletes were experienced in their respective modalities and they were familiar with treadmill (runners) and rowing ergometry (rowers) tests.

The tests for determination of the $\dot{V}O_2\text{max}$ were carried out in the Exercise Research Laboratory of the Physical Education School of the Federal University of Rio Grande do Sul, Brazil. The athletes participated in a progressive workload test until maximum effort, corresponding to the respective modality. Prior to the test, anthropometrical measurements were taken and a body composition evaluation was performed. The body density and percentage of fat were calculated using the protocols from Jackson and Pollock [10] and Siri [16], respectively.

The runners were recommended to perform a brief stretching exercise and, after having been fitted with a heart-rate monitor (Polar S-610) and a gas-collecting mask, they remained seated for roughly

TABLE 1. MEANS AND STANDARD DEVIATION FOR THE AGE, WEIGHT, HEIGHT AND $\dot{V}O_2\text{max}$ (ABSOLUTE AND RELATIVE)

	RUNNERS (11)	ROWERS (15)
Age (years)	22 + 10	24 + 5
Weight (kg)	61.7 + 9.3	83.5 + 7.2
Height (cm)	174 + 8.8	185.5 + 6.5
$\dot{V}O_2\text{max}$ absolute ($\text{l}\cdot\text{min}^{-1}$)	3.4 + 0.5	5.1 + 0.4
$\dot{V}O_2\text{max}$ relative ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	56.3 + 3.9	61.2 + 3.4

ten minutes prior to the start of the treadmill test. A progressive workload test was carried out on a treadmill (Quinton – Seattle, USA). The initial workload (velocity) was $9 \text{ km}\cdot\text{h}^{-1}$ with an increment of $0.5 \text{ km}\cdot\text{h}^{-1}$ each 30 seconds until maximum effort in order to determine the $\dot{V}O_2\text{max}$ and the allometric exponent. The workload increments were sufficient for a test duration of 8 -14 minutes.

The criteria used to determine the $\dot{V}O_2\text{max}$ were the same as those adopted by Hsi *et al.* [9], which consists of the observation of, at least, two of the following criteria: voluntary request by the subjects, plateau of the oxygen uptake curve and respiratory exchange ratio higher than 1.15.

The rowers performed a maximal test on a progressive rowing ergometer (Concept II - VT, USA) that lasted 5 minutes in each stage. The initial workload was 150 watts with increments of 50 watts for each stage. The test was stopped when the athlete reduced the rowing performance. The criteria utilized to determine the $\dot{V}O_2\text{max}$ were the same as those used for the runners. The workload increments were sufficient for a test of 8 -12 minutes.

In order to evaluate oxygen uptake, a mixing-box-type portable Aerosport KB1-C gas analyzer (Ann Arbor, USA) was used.

The allometric exponent was determined from the logarithmic equation $\text{Log } y = \text{Log } a + b \text{ Log } x$, where x is the body mass, y is the $\dot{V}O_2\text{max}$ ($\text{l}\cdot\text{min}^{-1}$), a is one constant and b is the allometric exponent. An average exponent was calculated for each group, using the average values of mass and $\dot{V}O_2\text{max}$. Thus, a linear equation was obtained together with its respective regression coefficient.

Descriptive statistics were used to analyze the collected data, which are presented as means and standard deviation for each group,

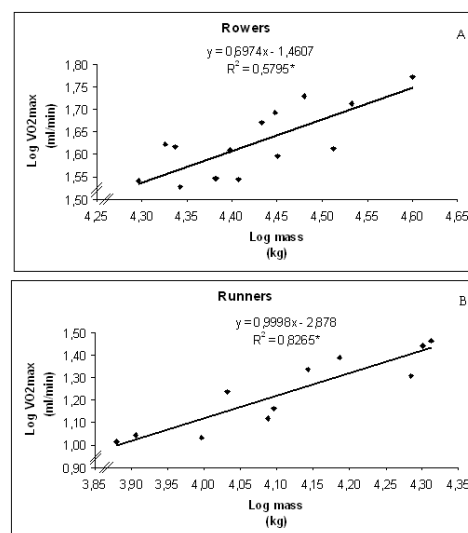


FIG. 1. EQUATION FOR ROWERS (A) AND RUNNERS (B) USED FOR DETERMINING THE ALLOMETRIC EXPONENT WITH $P < 0,05$.

Application of the allometric scale for the submaximal oxygen uptake in runners and rowers

TABLE 2. VALUE OF THE $\dot{V}O_{2\text{submax}}$ IN RUNNERS WITH AND WITHOUT THE USE OF THE ALLOMETRIC EXPONENT

RUNNERS (n=11)			
$\dot{V}O_{2\text{submax}}$ (l·min ⁻¹)		$\dot{V}O_{2\text{submax}}$ (ml·kg ^{-0.99} ·min ⁻¹)	
Runner 01	41.0	Runner 01	42.7
Runner 02	41.5	Runner 02	43.2
Runner 03	43.0	Runner 03	44.8
Runner 04	44.2	Runner 04	46.0
Runner 05	44.6	Runner 05	46.3
Runner 06	45.5	Runner 06	47.4
Runner 07	46.1	Runner 07	48.1
Runner 08	46.5	Runner 08	48.3
Runner 09	46.8	Runner 09	48.8
Runner 10	47.3	Runner 10	49.4
Runner 11	51.2	Runner 11	53.4

with and without the use of the allometric scale. The Shapiro-Wilk test of normality and Levene test of homogeneity were used. The independent T test was used in order to compare the percentage of fat between runners and rowers. The level of significance adopted in this study for all tests was =0.05 (SPSS version 13.0).

RESULTS

The main objective of the present study was to determine the allometric exponents for runners and rowers, which were verified in relation to their performance with and without the allometric application.

The allometric exponent of the rowers was 0.70, with confidence interval between 0.339 to 1.053, and of the runners was 1.00 (isometry), with confidence interval between 0.654 to 1.345, (Fig. 1).

The fat mass percentage of the rowers was 13.6±1.6 and of the runners was 11.9±1.4, with significant differences (p<0.05).

The results for performance with and without the use of the allometric exponent are shown in Tables 2 and 3.

All variables investigated in this study (including the logarithmic variables) were normal and homogeneous.

DISCUSSION

The results showed that the rowers had a higher percentage of fat and that this may have influenced the determined lower allometric exponent found in for this group, as was also observed in the study from Loftin *et al.* [13]. They observed the behavior of the peak values of the $\dot{V}O_{2\text{max}}$ in obese and non-obese girls with and without the use of the allometric exponent. The mean allometric exponent found for the non-obese girls was 0.92 while for the obese girls it was 0.46, suggesting an inverse relationship between the value of the allometric exponent and the percentage of fat. Without the use of the allometric exponent, the performance of both groups was similar. However, when the values of body mass were corrected by the

TABLE 3. VALUE OF THE $\dot{V}O_{2\text{submax}}$ IN ROWERS WITH AND WITHOUT THE USE OF THE ALLOMETRIC EXPONENT

ROWERS (15)			
$\dot{V}O_{2\text{submax}}$ (l·min ⁻¹)		$\dot{V}O_{2\text{submax}}$ (ml·kg ^{-0.66} ·min ⁻¹)	
Rower 01	36.5	Rower 01	146.5
Rower 02*	37.2	Rower 03	147.4
Rower 03*	37.6	Rower 04	149.8
Rower 04*	37.8	Rower 02	150.7
Rower 05	38.5	Rower 05	152.8
Rower 06*	39.1	Rower 07	153.3
Rower 07*	40.0	Rower 06	154.4
Rower 08	40.4	Rower 08	157.3
Rower 09*	41.0	Rower 10	160.9
Rower 10*	41.2	Rower 15	162.6
Rower 11*	42.1	Rower 14	163.6
Rower 12*	42.3	Rower 13	163.7
Rower 13*	42.6	Rower 12	164.5
Rower 14*	42.8	Rower 09	170.3
Rower 15*	42.9	Rower 11	172.8

Note: (*) Athletes with change in order of performance after application of allometric scale.

allometric method, the difference was 50% lower when the $\dot{V}O_{2}$ was seen in relation to the body mass.

Similarly, Kusano *et al.* [12] used the allometric scale to examine the effects of the body mass, the lean body mass and the percentage of fat in the performance of females in the indoor obstacles test of the United States Military Academy. They found a high relationship between exponents, absolute and relative body mass, and a proportional relationship between these two variables and the time required to complete the test. It is important to emphasize that these authors based their study on statistical analysis of correlation, while we attempted to find a single exponent that would serve different groups, with intra-group similarities in relation to the level and type of training and body composition, as in as the study of Loftin *et al.* [13]. However, the body composition represents the common ground between these studies. This is due to a tendency of the allometric exponent to decrease when the percentage of fat is higher, and a tendency to approximate the exponent of the unit when the lean mass content is higher. This can be attributed to the fact that fatty tissue is a metabolically less active, contributing less to performance during exercise.

In a previous study by our laboratory, Tartaruga *et al.* [17] highlight the importance of body surface in the development of different mechanical tasks, i.e., the manner by which the body mass of the subject (or animal) is supported during a task as well as the mechanical resistance offered by environment where the task is developed, may interfere in the determination of the allometric exponent. This could explain the low value of *b* for rowers and

the differences in percentage of fat. The rowers work in a seated position, unlike the runners, who need support their weight during the race.

Applying the allometric scale allows physiological variables of a specific group to be analyzed taking into consideration their characteristics. Chamari *et al.* [3] collected data for $\dot{V}O_{2\max}$ and $\dot{V}O_{2\text{submax}}$ in soccer players and young adults and found a single allometric exponent for the two groups with respect to two variables (for $\dot{V}O_{2\max}$ $b=0.72$ and for $\dot{V}O_{2\text{submax}}$ $b=0.60$). Differences were found when the $\dot{V}O_{2}$ values obtained using the traditional method were compared with those obtained with the application of the allometric scale. In the traditional method, the $\dot{V}O_{2\max}$ of adults was underestimated, but no difference was found with respect to young people. However, it was 5% higher when applied the allometric exponent of 0.72. The $\dot{V}O_{2\text{submax}}$ of young people was underestimated by 13% when analyzed in the traditional form, though there was no difference from adults when analyzed using the allometric method.

In Tables 2 and 3, rowers and runners, respectively, are shown in order of performance according to $\dot{V}O_{2\text{submax}}$ values, i.e., from the most economical to the least economical. For runners, the relations and proportions of performance after the application of allometric scale were retained due to the b found for this group, which is very close to the unit. On other hand, among the rowers, with the application of allometric scale, some inversions of the order of performance can be seen in some athletes. Rowers 8 and 9, for example, have values close to $\dot{V}O_{2\text{submax}}$ when compared to the traditional method. Nevertheless, from the allometric point of view, while rower 8 remained in the same place in the ranking, the rower 9 became the second least economic in the group.

Given these results, there arises a debate on the assessment of the performance of athletes, excluding the technical issues relating to each modality, as the application of the allometric scale allows physiological variables of a specific group to be analyzed while taking into consideration their characteristics, such as body composition, body surface area, level of training, environment of activity, etc [17].

CONCLUSIONS

The application of the allometric scale allows the specific characteristics of the sport practiced by the athlete to be taken into consideration, so that his/her physical condition can be better assessed. Thus, it may be used as a means of investigating, for example, why athletes with very similar physiological values perform so differently in races or, conversely, why athletes with different physiological values produce similar performances, so making it one more evaluation method to be used by coaches.

On some occasions, athletes from the same team have very similar physiological and technical characteristics, though one may perform better than another, even when there is no significant difference in $\dot{V}O_{2\text{submax}}$ and, possibly, economy of movement. The allometric scale can facilitate inter-comparison of the subjects.

Scaling may help both in understanding variation in aerobic power and in defining the physiological limitations of work capacity.

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REFERENCES

- Balady G.J., Berra K.A., Golding L.A., Gordon N.F., Mahler D.A., Myers J.N., Sheldahl L.M. Guidelines for Exercise Testing and Prescription. ACSM, 2000.
- Brisswalter J., Legros P., Durand M. Running economy, preferred step length correlated to body dimensions in elite middle distance runners. *J. Sports Med. Phys. Fitness* 1996;36:7-15.
- Chamari K., Moussa-Chamari I., Boussaidi L., Hachana Y., Kaouech F., Wisloff U. Appropriate interpretation of aerobic capacity: allometric scaling in adult and young soccer players. *Br. J. Sports Med.* 2005;39:97-101.
- Daniels J., Oldridge N., Nagle F., White B. Differences and changes in $\dot{V}O_2$ among young runners 10 to 18 years of age. *Med Sci Sports* 1978;10:200-203.
- Darveau C.A., Suarez R.K., Andrews R.D., Hochachka P.W. Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature* 2002;417(6885):166-170.
- Denadai B.S. Consumo máximo de oxigênio: fatores determinantes e limitantes. *Rev. Brasileira Atividade Fís. Saúde* 1995;1:85-94.
- Gilloloy J.F., Brown J.H., West G.B., Savage V.M., Charnov E.L. Effects of size and temperature on metabolic rate. *Science* 2001;293(5538):2248-2251.
- Goosey-Tolfrey V.L., Batterham A.M., Tolfrey K. Scaling behavior of $\dot{V}O_{2\text{peak}}$ in trained wheelchair athletes. *Med. Sci. Sports Exerc.* 2003;35:2106-2111.
- Hsi W.L., Lan C., Lai J.S. Normal standards for cardiopulmonary responses to exercise using a cycle ergometer test. *J. Formos Med. Assoc.* 1998;97:315-322.
- Jackson A.S., Pollock M.L. Generalized equations for predicting body density of men. *Br. J. Nutr.* 2001;40:497-504.
- Jensen K., Johansen L., Secher N.H. Influence of body mass on maximal oxygen uptake: effect of sample size. *Eur. J. Appl. Physiol.* 2001;84:201-205.
- Kusano M.A., Vanderburgh P.M., Bishop P. Impact of body size on women's military obstacle course performance. *Biomed. Sci. Instrum.* 1997;34:357-362.
- Loftin M., Sothorn M., Troscclair L., O'hlanon A., Miller J., Udall J. Scaling $\dot{V}O_2$ peak in obese and non-obese girls. *Obes. Res.* 2001;9:290-296.
- Powers S.K., Howley E.T. Exercise Physiology: theory and application to fitness and performance. 4 Ed. Mc Grall Hill, Boston 2000.
- Saltin B., Astrand P.O. Maximal oxygen uptake in athletes. *J. Appl. Physiol.* 1967;23:353-358.
- Siri W.E. Body composition from fluid spaces and density. National academy of science. Washington, USA, 1961.
- Tartaruga M.P., Peyré-Tartaruga L.A., Coertjens M., Medeiros M.H.D., Krueel L.F.M. The influence of the allometric scale on the relationship between running economy and biomechanical variables in distance runners. *Biol. Sport* 2009;26:263-273.
- West G.B., Brown J.H., Enquist B.J. A general model for the origin of allometric scaling laws in biology. *Science* 1997;276(5309):122-126.
- White C.R., Seymour R.S. Sample size and mass range effects on the allometric exponent of basal metabolic rate. *Comp. Biochem. Physiol. A* 2005;142:74-78.

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THE INFLUENCE OF THE ALLOMETRIC SCALE ON THE RELATIONSHIP BETWEEN RUNNING ECONOMY AND BIOMECHANICAL VARIABLES IN DISTANCE RUNNERS

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Abstract. Studies have demonstrated the need for the use of parameters that diminish the effect of body mass, for intra and inter group comparison, in individuals with different masses in order to provide a different analysis on the behaviour of the relation between running economy (RE) and biomechanical variables (BVs). The allometric scale is represented by a regression equation that indicates the behaviour of a physiological variable in relation to the variable mass ($RE=a \cdot x^b$), where x is body mass in (kg) and the dimensionless coefficient a is characteristic of the species analysed, and the dimensionless exponent b determines the percentage of mass to be associated with the physiological variable. The influence of the allometric scale ($b=-1; -0.75; -0.73; -0.67$) on the relationship between RE and BVs - stride length (SL), relative stride length (RSL), stride rate (SR), stride time (ST), support time (SUPT) and balance time (BALT) - at $12 \text{ km} \cdot \text{h}^{-1}$, was analysed in nine elite runners. Factorial analysis and Pearson's Correlation Coefficient test (r) with $P < 0.05$ were used. A decrease in the explanation power of the RE was observed, with the use of the allometric exponent, due to the BVs, as well as a reduction of the correlation coefficients between SL versus RE, ST versus RE and SR versus RE. The BALT presented a higher correlation where $b=-0.75$. The RSL and SUPT presented non-significant correlations. The variables SL, ST, SR and BALT were the most effective predictors of the RE, Where: $b=-1$, the allometric scale was most efficient to predict the running performance.

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Key words: Running economy - Allometric scale - Biomechanical variables

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Introduction

An organism with a greater mass presents a higher metabolic rate than an organism with a smaller body mass, as there is an increasing proportional relationship between mass and metabolism [8]. It may, however, present smaller physiological values than the smaller organism, where the values of this variable are normalized based on the body mass values [11,15]. In the first case, the metabolic rate will be expressed in an absolute form, by means of a unit that represents the total quantity of the variable for each kilogram of body mass (kg^{-1}).

The oxygen uptake divided by the total mass of the individual may yield a result that contrasts with other data, because it leads to the assumption that heavier athletes with lower relative submaximal oxygen uptake ($\text{VO}_{2\text{submax}}$) are more economical at a given velocity, as they need to consume less energy. Accordingly, the need to carry out comparisons of physiological variables between organisms belonging to the same group, or between different groups, may lead us to diverse assertions based on results that can be altered according to the manner by which the body mass of these organisms is associated with the physiological variables to be analysed [3].

Brisswalter [3], West [22] and Darveau [6] point out the need to use parameters that lessen the effect of body mass when comparing intra and inter groups with individuals of different body masses, in order to permit a different analysis of the phenomenon. An example of this is the allometric scale. It is represented by means of a regression equation that indicates the behaviour of a physiological variable y in relation to the variable mass x ($y=a \cdot x^b$), where coefficient a is characteristic of the class analysed and the b (allometric exponent) determines the percentage of mass to be associated with variable y .

A few studies have focussed on determining the exponent that best represents the percentage of body mass required for carrying out comparisons of the y variable by minimizing the effect of the difference in mass. To this end, such research projects have made use of studies related to the metabolic assessment of different animal species [6,24]. The work of Rubner apud White and Seymour [23], dated from the late XIX century, claimed an association of metabolic rate with $2/3$ of the individual's body mass (0.67). Svedenhag and Sjödin [20] found allometric exponents between 0.73 and 0.75 in distance runners and marathon runners, demonstrating an influence of the allometric scale on $\text{VO}_{2\text{submax}}$.

In the practice of sports, other studies have equally verified the need for utilizing different values, such as coefficients, for determining the percentage of total body mass to be considered. These values would be specific for different

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sports [11], as well as for wheelchair users [9]. Therefore, the purpose of this study was to analyze the influence of the allometric scale on the relationship between running economy (RE) and biomechanical variables (BVs), at submaximal running intensity.

Materials and Methods

Nine female elite runners, (5 distance runners and 4 long distance runners), with more than 5 years professional experience, from the Porto Alegre Gymnastics Society, were voluntarily recruited. All have attended the Exercise Research Laboratory of the Federal University of Rio Grande do Sul (Brazil) in order to complete the forms with their personal details and informed consent term, which is in accordance with the recommendations of the American College of Sports Medicine (ACSM), proposed in 1991 [1].

Firstly, the maximal oxygen uptake test (VO_{2max}) (Test 1) was carried out in order to characterize the sample. The RE test (Test 2) was carried out with a minimum two-day interval. The ambient temperature oscillated between 22°C-24°C.

For both tests all the subjects were instructed to wear the same type of training shoe (rubberized footwear without spikes,) and all had experience in treadmill running.

The subjects were instructed to fast two hours prior to each testing session. There was no intake of any kind of energetic substance during the tests.

Test 1: Maximal oxygen uptake (VO_{2max}) determination test: The subjects were recommended to perform a brief stretching session and, after having been fitted with a heart rate monitor (HRM) and a gas-collecting mask, they remained seated for roughly three minutes prior to the start of the test.

In this experiment, a progressive workload test, using ramp mode, was carried out on a treadmill. The initial workload (velocity) was 9 km·h⁻¹, with an increment of 0.5 km·h⁻¹ every 30 seconds. The workload increments were sufficient for test duration of 8-14 minutes. The ramp mode facilitates the visualization of the ventilatory thresholds (VT) and, in addition it is effective for determining VO_{2max} .

The criteria utilized to determine the VO_{2max} were the same adopted by His [10], which consists of the observation of, at least, two of the following criteria:

- voluntary selection of the subjects;
- plateau of the oxygen uptake curve (VO_2);
- respiratory exchange ratio higher than 1,15

During the tests, the subjects did, at any time support themselves on the

treadmill for support.

Test 2: Running Economy (RE) determination test: The RE has been defined as the steady state of $VO_{2submax}$ for a velocity [5]. In order to determine the RE, an adaptation of the protocol proposed by [19] was carried out, which consists of a stage of the 7 minutes. In the present study, this was changed to 6 minutes due to the possibility of the stabilization of VO_2 at three minutes, allowing for a $VO_{2submax}$ plateau in providing the RE information [2]. The $VO_{2submax}$ was determined from the mean values that were found between 5 to 6 minutes. The total duration of the test was 6 minutes for each individual. The respiratory switch ratio did not exceed 0.95.

Firstly, the subjects performed a warm-up session consisting of stretching and run at $9 \text{ km}\cdot\text{h}^{-1}$, for 3 minutes. Then, the subjects performed a submaximal 6 minutes at $12 \text{ km}\cdot\text{h}^{-1}$ (85% of VO_{2max}). This velocity was chosen for three reasons: 1) at $12 \text{ km}\cdot\text{h}^{-1}$ the subjects presented RE values situated at an intermediary zone between the first and the second ventilatory threshold, which is ideal for the analysis of the running economy [19]; 2) McMiken and Daniels [17] showed that there is no significant difference between the aerobic requirement in treadmill running, above 73% of VO_{2max} and ground running; and 3) $12 \text{ km}\cdot\text{h}^{-1}$ corresponds to a velocity adopted by the literature for RE analysis [13,18,19].

During the economy test, the individual's left sagittal plane was videotaped using a Pulnix F4 video camera with a sampling rate of 120 frames per second and a shutter velocity of 1/1000th per seconds, where three gait cycles were recorded. The camera was positioned three meters from the subject to be assessed and one meter above ground-level.

Once the RE and BVs values had been determined, an analysis of the influence of the allometric scale ($b=-1$; -0.75 ; -0.73 ; -0.67) on the relationship between the RE and the BVs – stride length (SL), stride length relative to the length of the left lower limb (RSL), stride rate (ST), support time (SUPT) and balance time (BALT) – was carried out. The distance between the lateral malleolus of the fibula and the femoral greater trochanter was considered the length of the left lower limb [21]. The following mathematical formula was applied in order to acquire the RE values with the allometric exponents under consideration.

$$RE = a \cdot x^b \cdot 1000$$

where:

RE: running economy values with allometric exponent (b)

a: $VO_{2submax}$ ($\text{ml}\cdot\text{min}^{-1}$)

x: body mass (kg)

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The SL was determined from the classical running formula ($v = SL \times SR$), by dividing the horizontal velocity by the stride rate. The ST was determined through the summing up of the frames from a complete stride cycle and then multiplied by 8.33×10^{-3} (estimated frame time). The SUPT and BALT were determined by means of the visual analysis of the beginning and completion of the support phase through visual analysis of the spatial model.

Statistical analysis: All the variables (RE and BVs) were tested in relation to their normality, that is, the similarity of their distributions in relation to the Gaussian distribution, by means of a Shapiro-Wilk test. The homogeneity of the variance was assessed using Levene's test. The results showed significance indices higher than 0.05, indicating normal distribution, allowing for the use of parametric statistical tests [18].

Descriptive statistics were carried out through the mean and standard deviations.

In an effort to reduce the number of variables in dimensions in order to better explain the variability of the phenomenon under consideration, factorial analysis of the main components was performed on the different percentages of body mass. The main components are formed through the relationships between the variables. The cut-off value for the extraction of the component for each factor was 0.50. Pearson's Correlation Coefficient test (r), with $P < 0.05$, was applied to verify the existence of an association between the variables RE versus BVs, in the different body mass percentages.

Results

The physical and physiological characteristics are presented in Table 1.

Table 1
Physical characteristics of the subjects; values are means and SEM

Variables n=9	c	d	SEM	95% of confidence interval of the median		Min	Max
				Lower Limit	Upper Limit		
Age (years)	26.00	±14.58	4.86198	14.78824	37.2117	13.00	50.00
Height (cm)	160.83	±6.18	0.02062	156.0789	165.5877	153.00	171.00
Weight(kg)	50.16	±7.96	2.65288	44.0491	56.2842	33.40	59.20
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	43.14	±4.08	1.35914	40.0103	46.2786	36.70	51.00

The results of the factorial analysis of the main components are shown in Table 2.

Table 2
Explanation of the variance of biomechanical variables using the allometric scale

Allometric scale	Factor	Proper values			Extraction of sums of frames		
		Total	% of variance	% accumulated	Total	% of variance	% accumulated
-1	1	5.303	75.759	75.759	5.303	75.759	75.759
-0.75	1	5.244	74.916	74.916	5.244	74.916	74.916
-0.73	1	5.219	74.566	74.564	5.219	74.564	74.564
-0.67	1	5.159	73.695	73.695	5.159	73.695	73.695

By analysing the results in Table 2, a decrease can be observed in the explanation power of the variability of the BVs by means of the allometric scale, through exponential values ($b=-1$; -0.75 ; -0.73 ; -0.67). These results demonstrate that, in the group under analysis, the allometric scale was more effective in predicting the running performance where $b=-1$.

In Table 3, decreases in the correlation coefficients between SL vs $VO_{2submax}$; ST vs $VO_{2submax}$, and SR vs $VO_{2submax}$ with the use of the allometric scale. Where $b=-0.75$, BALT showed a higher correlation coefficient. The SL and SUPT showed insignificant correlations. Of the four exponential values under analysis in this study, $VO_{2submax}$, where relativized at $kg^{-0.67}$, showed a lower influence on the relationship between RE vs BVs.

Table 3
Correlation coefficients between $VO_{2submax}$ vs BVs using the allometric scale

Allometric scale	Biomechanical variables					
	SL	ST	SR	BALT	RSL	SUPT
-1	-0.829*	-0.829*	0.790*	-0.697*	-0.438	-0.386
-0.75	-0.720*	-0.718*	0.707*	-0.814*	-0.617	0.119
-0.73	-0.699*	-0.698*	0.687*	-0.803*	-0.613	0.144
-0.67	-0.643	-0.640	0.636*	-0.777*	-0.608	0.214

Note: SL - stride length; ST - stride time; SR - stride rate; BALT - balance time; RSL - relative stride length; SUPT - support time; * $P<0.05$.

Discussion

Many authors have studied the influence of the allometric scale on the relationship between oxygen uptake and physical activity. Jensen *et al.* [11], analysing the VO_{2max} of the 967 athletes, representing 25 different sports, found different values for the allometric exponents (b) for each type of sport, with emphasis on the value $b=0.73$ for distance running and cycling types, which demonstrates that the allometric scale can be useful in understanding the variability of the maximal aerobic capacity and the physiological limitations of the working capacity.

In relation to the $VO_{2submax}$, Svedenhag and Sjödin [20] found allometric exponents between 0.73 and 0.75 at long distance runners, which demonstrates that the allometric scale can be applied to submaximal running intensities. Additionally, by analysing the allometric results from seven males and nine female cross-country athletes, resulting from the relationship between the peak oxygen uptake (VO_{2peak}) and body mass, Larsson *et al.* [14] found allometric exponents corresponding to 1 and 0.67, which demonstrates that gender may interfere with the relationship in question and, consequently, with the overall performance of such athletes.

The divergences found in the studies from Svedenhag and Sjödin [20], Jensen *et al.* [11] and Larsson *et al.* [14] demonstrate that allometry may yield different results, according to the type of sport analysed, the effort intensity exerted, gender and individual physical fitness. Moreover, they demonstrate that, as yet, there is no consensus in the literature concerning the use of the allometric scale, the exponential value to be utilized in a given situation, and particularly, regarding the causes leading to the utilization, or not, of a given allometric exponent.

In the biological field, the works by Rubner apud White and Saymour [23], dated from the late XIX century, claimed an association of the metabolic rate with $2/3$ of the individual's body mass (0.67). In 1932, Kleiber [12] raised the need for the exponent to be used to have a value higher than the one suggested by Rubner. Brody [4], corroborating the findings in Kleiber's studies, determines this exponent as being relative to $3/4$ (0.75) of the body mass. In 1997, West and associates [22] observed that the exponent $3/4$ could additionally be used in the comparison of vascular systems between diverse animal, microorganism and plant species. In 2002, Darveau and associates [6] advocated the need to use different exponents, specific for each physiological condition of the individual.

Allometric conditions have also been used by nutritionists in estimating calorie needs; by archaeologists, in estimating the body weight from the dimensions of bones found by anthropometrists, for determining body proportions; and by

physicians for estimating medication doses. While all the estimates derived from allometric equations may not necessarily be exact, they do permit an approximation that makes it possible to predict the variation that can be attributed to the body size [7].

Unlike the allometric values observed in previous studies, Brisswalter *et al.* [3], when analysing the influence of the allometric scale on the relationship between RE and the anthropometric measurements (body weight, fat percentage, height and leg length) from 28 (half-marathon runners), at two submaximal running intensities (9 and 12 km·h⁻¹), corresponding to an intensity below the anaerobic threshold, and the second very close to the threshold, found higher correlation when the athletes were running at 15 km·h⁻¹, regardless of the allometric coefficient used (b=1 and 0.75). The authors justify these outcomes in view of the speed of the trial, 9 km·h⁻¹, which corresponds to a very low competition speed which, in turn, corresponds to a biomechanical discomfort. In contrast, 15 km·h⁻¹ corresponds, precisely, to the competition speed of these athletes, at which greater physiological and biomechanical adaptation is achieved. Moreover, Brisswalter *et al.* [3] found that, at 15 km·h⁻¹ and where b=1, there was a greater influence of the allometric scale on the relationship between the RE and the anthropometric variables, especially related to body mass, height/stature and lower limb length. The authors believe that this outcome may be related to the fact that significant reverse correlations occurred between VO_{2submax} and the anthropometric variables. By relativizing VO₂ values with 100% of the body mass (b=1), a greater heterogeneity is yielded in RE values and, consequently, there is a greater chance of occurring greater correlations between VO_{2submax} and anthropometric variables.

While the authors do not demonstrate results referring to the absolute value of VO₂, it is believed that these results might be very similar among the subjects under analysis.

In this study, we found that, irrespective of the statistical analysis adopted (factorial analysis of the main components and/or linear correlation analysis), the influence on the relationship between the RE and BVs of the allometric exponent b corresponding to '1', was higher than the other allometric exponents that were used in this study, which corroborates the findings in the studies by Brisswalter *et al.* [3]. We believe that this outcome might be related to the heterogeneity of the anthropometric values (body weight and height) and, principally, the heterogeneous values of VO_{2submax} found at the submaximal running intensity adopted in this study (12 km·h⁻¹). Additionally, it was observed that, where b=0.67, two of the six correlations were not significant, demonstrating that the influence of body weight, as well as the overall anthropometric analysis of the analysed

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subjects, is important in the relationship between the RE and the BVs, since this relationship directly impacts the RE values.

The biomechanical variables that were most related to the RE were SL, ST, SR and BALT. Cavanagh and Kram [5], and Tartaruga *et al.* [21], found that stride length, stride rate and stride time were the biomechanical variables that most related to the RE.

Finally, Martin *et al.* [16] highlighted three issues that should be considered in choosing the allometric scale in studies with humans, so that the findings can be replicated more effectively: 1) taking into consideration the statistical measures and outliers when choosing of the allometric exponent; 2) recognition of the percentage of influence of the intervenient variables (e.g., anthropometric, psychological variables interfering with the outcomes of VO₂); 3) caution in the inference of the results obtained through the correlation analysis. According to the authors of this study, any of these issues can interfere with the allometric results obtained for a given group and, consequently, the chance of replication of these results is likely to be diminished.

Conclusion

The relationship between RE and BVs, in the group under analysis, was greater where the VO_{2submax} values were relativized at 100% of the body mass, that is, where $b=1$ the allometric scale was more effective in predicting the running performance. However, anthropometric measures, statistical analyses, as well as the type of sport under analysis, exertion intensity, gender and the individual physical fitness, can impact on the determination of allometric coefficient values to be used in each study. It is suggested that further studies on the subject be undertaken.

References

1. American College of Sports Medicine (1991) Guidelines for Exercise Testing and Prescription. 4 Ed. Lea and Febiger, PA
2. Basset DR Jr, E.T.Howley (2000) Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med.Sci.Sports Exerc.* 32:70-84
3. Brisswalter J, P.Legros, M.Durand (1996) Running economy, preferred step length correlated to body dimensions in elite middle distance runners. *J.Sports Med.Phys.Fitness* 36:7-15
4. Brody S. (1945) Bioenergetics and Growth. Reinhold, New York

5. Cavanagh P.R., R.Kram (1985) The efficiency of human movement-a statement of the problem. *Med.Sci.Sports Exerc.* 17:304-308
6. Darveau C.A, R.K.Suarez, R.D.Andrews, P.W.Hochchka (2002) Allometric cascade as a unifying principle of body mass effects on metabolism. *Nature* 417:166-170
7. De La Rosa, Fjbd, C.R.Rodríguez-Añez (2002) O estudo das características físicas do homem por meio da proporcionalidade. *Revista Brasileira de Cineantropometria e Desempenho Humano* 1:53-66
8. Gillooly J.F., J.H.Brown, G.B.West, V.M.Savage, E.L.Charnov (2001) Effects of size and temperature on metabolic rate. *Science* 293:2248-2251
9. Goosey-Tolfrey V.L., A.M.Batterham, K.Tolfrey (2003) Scaling behavior of VO_{2peak} in trained wheelchair athletes. *Med.Sci.Sports Exerc.* 35:2106-2111
10. His W.L., C.Lan, J.S.Lai (1998) Normal standards for cardiopulmonary responses to exercise using a cycle ergometer test. *J.Formosan Med.Assoc.* 97:315-322
11. Jensen K, L.Johansen, N.H.Secher (2001) Influence of body mass on maximal oxygen uptake: effect of sample size. *Eur.J.Appl.Physiol.* 84:201-205
12. Kleiber M. (1932) Body size and metabolism. *Hilgardia* (6):315-353
13. Kyröläinen H., A.Belli, P.V.Komi (2001) Biomechanical factors affecting running economy. *Med.Sci.Sports Exerc.* 33:1330-1337
14. Larsson P., P.Olofsson, E.Jakobsson, L.Burlin, K.Henriksson-Larsén (2002) Physiological predictors of performance in cross-country skiing from treadmill test in male and female subjects. *Scand.J.Med.Sci.Sports* 12:347-353
15. Loftin M., M.Sothern, L.Trosclair, A.O'Hanlon, J.Miller, J.Udall (2001) Scaling VO_{2peak} in obese and non-obese girls. *Obes.Res.* 9:290-296
16. Martin R.D., M.Genoud, C.K.Hemelrijk (2005) Problems of allometric scaling analysis: examples from mammalian reproductive biology. *J.Exp.Biol.* 200:1731-1747
17. McMiken D.F., J.T.Daniels (1976) Aerobic requirement maximal aerobic power in treadmill and track running. *Med.Sci.Sports Exerc.* 8:14-17
18. Pestana M.H., E.Gageiro Jr. (1998) Análise de dados para ciências sociais: a complementaridade do SPSS, Lisboa
19. Powers S., S.Dodd, R.Deason, R.Byrd, T.McKnight (1983) Ventilatory threshold, running economy, and distance running performance of trained athletes. *Res.Q.Exerc.Sport* 54:179-182
20. Svedenhag J., B.Sjödin (1994) Body mass modified running economy and step length in elite male middle and long distance runners. *Int.J.Sports Med.* 15:305-310
21. Tartaruga L.A.P., M.P.Tartaruga, J.L.Ribeiro, M.Coertjens, L.R.Ribas, L.F.M.Kruel (2004) Correlações entre economia de corrida e variáveis cinemáticas em corredores de alto nível. *Revista Brasileira de Biomecânica* 9:51-58
22. West G.B, J.H.Brown, B.J.Enquist (1997) A general model for the origin of allometric scaling laws in biology. *Science* 276:122-126
23. White C.R., R.S.Seymour (2005) Allometric scaling of mammalian metabolism. *J.Exp.Biol.* 208:1611-1619



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24. White C.R., R.S.Seymour (2003) Mammalian basal metabolic rate is proportional to body mass^{2/3} *PNAS* 100:4046-4049

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ARTIGO ORIGINAL

RELAÇÃO ENTRE CONSUMO MÁXIMO E SUBMÁXIMO DE OXIGÊNIO EM CORREDORES E REMADORES DE RENDIMENTO

Relation between submaximum and maximum oxygen uptake of elite distance runners and elite rowers

Marcus Peikriszwili Tartaruga, Débora Dutra Beilke, Marcelo Coertjens, Rafael Reimann Baptista, Leonardo Alexandre Peyré Tartaruga, Luiz Fernando Martins Kruel

Resumo

O objetivo do estudo foi relacionar o consumo de oxigênio no limiar anaeróbio (VO_{2la}) com o consumo máximo de oxigênio ($VO_{2máx}$) de corredores e remadores de rendimento, a partir da relativização do VO_2 absoluto, pela massa corporal total, pelo expoente alométrico e pela massa magra. Dez corredores e quinze remadores realizaram um teste progressivo máximo. Para os corredores, a velocidade inicial foi de 10 km h^{-1} , com incremento de $0,5\text{ km h}^{-1}$ a cada 30s. Para os remadores, a carga inicial foi de 150w, com incremento de 50w a cada minuto. Para ambos os grupos, o $VO_{2máx}$ e o VO_{2la} foram determinados pela análise das respostas ventilatórias. Para os remadores, especificamente, também foi utilizado o comportamento da curva de lactato vs potência. Foi feita análise de normalidade e homogeneidade (Shapiro-Wilk e Levene), teste *t-Student* para amostras independentes e correlação Produto Momento de Pearson, com $p < 0,05$. Foram verificadas boas correlações ($r > 0,5$) entre o VO_{2la} e o $VO_{2máx}$ nos corredores, em todas as formas de expressão do VO_2 : massa corporal total e expoente alométrico de 0,968 ($r=0,70$) e massa magra ($r=0,74$). Baixas correlações foram verificadas nos remadores, quando o VO_2 foi determinado pela curva de lactato: massa corporal total e massa magra ($r=0,26$) e expoente alométrico de 0,690 ($r=0,07$). Porém, quando o VO_2 foi determinado pelas respostas ventilatórias, houve boas correlações: massa corporal total ($r=0,64$), expoente alométrico de 0,690 ($r=0,54$) e massa magra ($r=0,60$). Os resultados mostram que a relação entre VO_{2la} e o $VO_{2máx}$, de ambos os grupos, possuem o mesmo comportamento, independente da forma de relativização do VO_2 . Mas, a forma de determinação do VO_2 pode ser uma variável importante na relação entre VO_{2la} e $VO_{2máx}$.

Palavras-chave: Consumo de Oxigênio, Limiar Anaeróbio, Desempenho.

Abstract

The objective of the study was to relate the oxygen uptake in the anaerobic threshold (VO_{2la}) and the maximum aerobic power (VO_{2max}) of elite distance runners and elite rowers of income from the relativization of the absolute VO_2 for the body mass, expoent allometric and lean mass. Ten runners and fifteen rowers had executed gradual a maximum test. For the runners, the initial velocity was of 10 km h^{-1} , with increment of $0,5\text{ km h}^{-1}$ to each 30s. For the rowers, the initial load was of 150w, with increment of 50w to each minute. For both groups, the VO_{2max} and the VO_{2la} had been determined by the analysis of the ventilation. For the rowers, specifically, also the behavior of the lactate curve was used versus power. It was made analysis of normality and homogeneity (Shapiro-Wilk and Levene), test *t-Student* for independent samples and correlation Product Moment of Pearson, with $p < 0.05$. Good correlations had been verified ($r > 0.5$) between VO_{2la} and the VO_{2max} in the runners, in all the forms of expression of the VO_2 : body mass and expoent allometric of 0.968 ($r=0.70$) and lean mass ($r=0.74$). Low correlations had been verified in the rowers when the VO_2 was determined by the lactate curve: body mass and lean mass ($r=0,26$) and expoent allometric of 0.690 ($r=0.07$). However, when the VO_2 was determined by the ventilation, it had good correlations: body mass ($r=0.64$), expoent allometric of 0.690 ($r=0.54$) and lean mass ($r=0.60$). The results show that the relation between VO_{2la} and the VO_{2max} of both the groups possess behavior the same, independent of the form of relativization of the VO_2 . But the form of determination of the VO_2 can be an important variable in the relation between VO_{2la} and VO_{2max} .

Key words: Oxygen Uptake, Anaerobic Threshold, Performance.

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INTRODUÇÃO

Desde 1923, ano em que Archibald Vivian Hill e Hartley Lupton ganharam o prêmio Nobel, o consumo de oxigênio (VO_2) passou a ter presença freqüente em publicações sobre as respostas fisiológicas durante o exercício (Silva e Oliveira, 2004). Tal interesse se justifica pela associação do VO_2 , em esforço submáximo e máximo, com dimensões de saúde e de rendimento desportivo (Saltin e Astrand, 1967). Os modelos apresentados, há mais de oito décadas, têm sido intensamente rediscutidos nos últimos quinze anos, justificando abordagens sobre o estado da arte existente sobre esta variável (Silva e Oliveira, 2004).

Atualmente, o VO_2 , medido inicialmente de forma absoluta, tem sido expresso de diferentes formas. Medidas relativas à massa corporal total e a um percentual dessa massa (coeficientes alométricos diferentes de 1) têm sido adotadas, objetivando uma real comparação do condicionamento físico entre sujeitos (Svedenhag e Sjodin, 1994; Svedenhag, 1995; Vanderburgh e Dooman, 2000), principalmente devido ao fato de existirem muitos tipos de locomoção, requerendo, cada um, uma massa corporal a ser movida (Saltin e Astrand, 1967). De acordo com Denadai (1995), valores relativos são mais utilizados para comparações entre indivíduos que diferem na massa corporal total, na massa magra, na estatura e no percentual de gordura, pois a musculatura envolvida na atividade influencia nessas variáveis.

Em um estudo desenvolvido por Bergh et al. (1991), que analisou a relação entre o VO_2 e a massa corporal total de 151 jovens corredores de rendimento, verificaram uma forte relação entre essas variáveis, sugerindo o uso da massa corporal total como variável de relativização do VO_2 em jovens corredores.

Entretanto, diversos autores, como Winter e Hamley (1976), Svedenhag e Sjodin (1994), Brisswalter et al. (1996), Jensen et al. (2001) e Loftin et al. (2001), têm demonstrado que a massa corporal total pode subestimar os valores reais de VO_2 , influenciando nas comparações entre sujeitos.

Desta forma, alguns autores, como Brisswalter et al. (1996), West et al. (1997) e Darveau et al. (2002), apontam para a necessidade da utilização de parâmetros permitindo que variáveis fisiológicas, como o VO_2 , sejam comparadas entre indivíduos com massas diferentes. A escala alométrica é um exemplo. Ela é representada por uma

equação de regressão, que indica o comportamento de uma variável fisiológica “Y” em relação à variável massa “X” ($Y = aX^b$). O coeficiente “a” é característico da espécie analisada, podendo ser o consumo máximo de oxigênio ($VO_{2máx}$) absoluto. O expoente “b” determina o percentual da massa a ser associado com a variável “Y”, sendo denominado expoente alométrico. Esta função exponencial pode ser transformada, logaritmicamente, na função linear: $\text{Log } y = \text{Log } a + b \text{ Log } x$.

Já a massa magra, também, tem sido utilizada como parâmetro de relativização do VO_2 , principalmente em intensidades submáximas. Em um estudo desenvolvido por Winter e Hamley (1976), analisando a influência da massa magra nos resultados de economia de corrida (ECO) de 32 corredores de rendimento, foram verificadas boas correlações ($r > 0,6$) entre essas variáveis, em diferentes velocidades de corrida, demonstrando que quanto maior a velocidade de corrida, maior a influência da massa magra nos valores de ECO. De acordo com Powers et al. (1983), Kyrolainen et al. (2001) e Nummela et al. (2006), a ECO consiste no consumo submáximo de oxigênio ($VO_{2submáx}$), para uma determinada velocidade submáxima de corrida. O mesmo conceito pode ser utilizado para outras modalidades esportivas (economia de nado e economia de movimento).

Tanto o $VO_{2máx}$, como a economia de movimento, têm sido considerados importantes na predição da *performance* de atividades desportivas com predomínio aeróbio, como na corrida e no remo. Se um grupo de pessoas apresenta uma alta variação de aptidão física (sedentários e atletas de elite), o $VO_{2máx}$ é a variável mais preditiva para determinar o resultado em provas de resistência. No entanto, importantes variações têm sido encontradas entre corredores com $VO_{2máx}$ similares (Sjodin e Svedenhag, 1985). É possível existir uma grande variação no desempenho entre corredores de mesmo $VO_{2máx}$ (Conley e Krahenbuhl, 1980; Sjodin e Svedenhag, 1985; Svedenhag e Sjodin, 1994). Relativamente baixos valores de $VO_{2máx}$ têm sido encontrados entre maratonistas de alto nível. Desta forma, o limiar anaeróbio (LA) parece possuir uma importância considerável na predição do rendimento de corredores de meia e longa distâncias (Denis et al., 1982; Kumagai et al., 1982; Yoshida et al., 1987; Daniels e Daniels, 1992; Novacheck, 1998; Meyer et al., 2003), bem como em atividades desportivas com predomínio aeróbio, como a natação, o ciclismo e o remo. A intensidade de

TABELA 1
MÉDIA E DESVIO-PADRÃO DAS VARIÁVEIS: IDADE, MASSA CORPORAL, ESTATURA E CONSUMO MÁXIMO DE OXIGÊNIO RELATIVO.

	CORREDORES (10)	REMADORES (15)
IDADE (anos)	22,3 ± 10,4	24 ± 5,4
MASSA CORPORAL (kg)	61,7 ± 9,3	83,5 ± 7,2
ESTATURA (cm)	174,1 ± 8,8	185,5 ± 6,5
VO _{2máx} (ml.kg ⁻¹ .min ⁻¹)	57,2 ± 3,4	61,0 ± 3,4

exercício, necessária para obter a maior concentração constante de lactato sanguíneo, tem sido correlacionada com a *performance* de corrida (Costill, 1972; Farrell et al., 1979). Obviamente, outros fatores também influenciam no desempenho da resistência cardiorrespiratória (Denis et al., 1982; Kumagai et al., 1982; Yoshida et al., 1987; Daniels e Daniels, 1992; Novacheck, 1998; Meyer et al., 2003; Tartaruga et al., 2004).

A relação entre o consumo de oxigênio, no limiar anaeróbico (VO_{2la}), e o VO_{2máx} tem sido investigada, desde a década de 70, por Weltman e Katch (1979). De acordo com estes autores, a predição do VO_{2máx} pelo VO_{2la} pode ser de até 89% para sujeitos bem condicionados, destacando que a referida relação deve ser analisada do ponto de vista da acidose metabólica, e não do metabolismo causado pela hipoxia. Esta afirmação corrobora com os achados de Davis et al. (1976), onde os autores verificaram uma forte correlação entre o VO_{2la}, determinado pela ventilação e pela lactacidemia ($r = 0,95$).

Apesar de todas as formas de relativização do VO₂, em situações máximas e submáximas de esforço, nenhum estudo tem sido desenvolvido analisando qual das formas de relativização implica em uma melhor relação entre VO_{2la} e VO_{2máx}. Desta forma, o objetivo do estudo foi relacionar o VO_{2la} e o VO_{2máx} de corredores e remadores de rendimento, a partir da relativização do VO₂ absoluto, pela massa corporal total, pelo expoente alométrico e pela massa magra.

METODOLOGIA

A amostra foi composta de 10 corredores meio-fundistas longos (1.500 a 3.000m), da Sociedade Ginástica de Porto Alegre (SOGIPA), e 15 remadores da classe sênior A, pertencentes à equipe de remo do Grêmio Náutico União

de Porto Alegre (GNU) (TABELA 1). Todos os atletas, selecionados por voluntariedade, eram do sexo masculino, saudáveis e com mais de três anos de experiência em provas de rendimento, em nível regional, nacional e internacional. Antes do início das avaliações, todos os indivíduos leram e assinaram o termo de consentimento livre e esclarecido, no qual constavam todas as informações pertinentes ao estudo referente à cada avaliação, sendo estas aprovadas pelo Comitê de Ética em Pesquisa da Universidade Federal do Rio Grande do Sul.

Os testes para determinação do VO_{2máx} foram realizados no Laboratório de Pesquisa do Exercício (LAPEX), da Escola de Educação Física da Universidade Federal do Rio Grande do Sul (EsEF – UFRGS). Os atletas participaram de um teste progressivo máximo, correspondente à modalidade esportiva. No mesmo dia, foi feita uma avaliação da composição corporal e verificação das medidas antropométricas. O percentual de gordura corporal (%G) foi calculado através da fórmula de Siri (1961):

$$\%G = (495/D) - 450$$

Para o cálculo da densidade corporal (D), foi utilizada a equação desenvolvida por Jackson e Pollock (1978), validada por Petroski (1995), para homens com idade entre 18 e 61 anos, utilizando sete dobras cutâneas e os perímetros do abdome e antebraço.

$$D = 1,101 - 0,0004115 * (S7DC) + 0,00000069 * (S7DC)^2 - 0,00022631 * (ID) - 0,0059239 * (PAB) + 0,0190632 * (PAT)$$

onde:

S7DC = somatório das dobras cutâneas: subescapular, tríceps, peitoral, axilar média, supra-iliaca, abdominal e coxa;

ID = idade (anos);

MC = massa corporal (kg); e

PAB e PAT = perímetros do abdome e antebraço (m).

As medidas de dobras cutâneas e perímetros foram feitas por um profissional de Educação Física com experiência em avaliações antropométricas.

Os corredores realizaram um breve alongamento e, após a colocação do cardiofreqüencímetro (Polar S-610) e da máscara de coleta de gases, ficaram sentados por, aproximadamente, 10 minutos antes do início do teste. Foi aplicado um teste em esteira rolante com cargas progressivas, no estilo rampa. A velocidade inicial foi de $10 \text{ km}\cdot\text{h}^{-1}$, com um incremento de $0,5 \text{ km}\cdot\text{h}^{-1}$, a cada 30 segundos, até a exaustão. Os testes duraram de doze a quatorze minutos. Os critérios utilizados para validação do teste, conforme Howley et al. (1995) e Hsi et al. (1998), foram: platô de consumo de oxigênio em dois estágios consecutivos, ou seja, mesmo com incremento da carga, não se observou aumento do consumo de oxigênio; e da taxa de troca respiratória ($QR > 1,1$), que é a relação entre a quantidade de gás carbônico produzido e o total do consumo de oxigênio.

Ambos os critérios deviam ser alcançados para a validação do teste.

Os indivíduos foram incentivados, verbalmente, para alcançarem a melhor *performance* no teste. Após a validação do mesmo, a velocidade da esteira foi diminuída, progressivamente, até que o indivíduo se sentisse recuperado o suficiente para sair da esteira.

Os remadores realizaram um teste máximo progressivo em remoergômetro (Concept II – VT, USA), com uma duração de estágios de cinco minutos. A carga inicial era de 150 Watts, com incremento de 50 Watts a cada estágio. O teste era interrompido quando o atleta referia não ter mais condições de manter a potência de remadas determinada. A freqüência cardíaca também foi monitorada.

Para ambos os grupos, o $\text{VO}_{2\text{máx}}$ e o $\text{VO}_{2\text{lia}}$ foram determinados pela análise das respostas ventilatórias, através de um analisador de gases, modelo MGC, da Medical Graphics Corporation (St. Paul, EUA). A freqüência de amostragem foi *breath-by-breath*. Utilizou-se um bocal

e um ocluser nasal, limitando a respiração do indivíduo apenas pela boca. Cada grupo desenvolveu os testes em dias alternados e no mesmo horário. Considerou-se o valor de pico como o $\text{VO}_{2\text{máx}}$.

Especificamente para os remadores, também, foi analisado o comportamento da curva de lactato vs potência, para determinação do limiar de lactato (LL). O sangue arterializado do lóbulo da orelha era coletado, durante 60 segundos, ao final de cada estágio, sendo analisado pelo lactímetro Accusport Roche. A utilização do lóbulo da orelha, como local de coleta de sangue, já foi anteriormente comparada com outras regiões em remadores, não tendo sido verificada diferença entre os locais de coleta (Forsyth e Farrally, 2000).

Os valores de VO_2 foram determinados de forma absoluta ($\text{l}\cdot\text{min}^{-1}$) e relativa, durante o LA e o máximo esforço. A relativização utilizada correspondeu à massa corporal total (método tradicional), ao expoente alométrico (método alométrico) e à massa magra, todos em $\text{l}\cdot\text{kg}^{-x}\cdot\text{min}^{-1}$, onde x corresponde ao valor referente à forma de relativização.

O LA, determinado pela ventilação, foi identificado por três fisiologistas do exercício, através da segunda quebra da curva de VE e equivalente respiratório – VE/VCO_2 . Quando dois, dos três fisiologistas, encontravam igual valor de limiar anaeróbio, o mesmo era considerado como sendo o limiar anaeróbio. Quando todos os fisiologistas encontravam diferentes valores de LA, o valor intermediário era considerado como sendo o LA. Já o LA, determinado pela lactacidemia (limiar de lactato), foi determinado empregando-se a metodologia descrita primeiramente por Cheng et al. (1992) e, posteriormente, também utilizada por Nicholson e Sleivert (2001) e intitulada de Dmáx (Distância máxima). Esse método foi assim batizado porque utiliza uma técnica em sua determinação, na qual uma curva é criada, plotando-se os valores de lactato sanguíneo, em um gráfico do Microsoft Excel, criando-se uma linha de tendência exponencial no mesmo. Feito isso, uma reta é traçada entre o ponto inicial e o final da curva de tendência, sendo a maior distância entre a reta traçada e a curva criada pelo gráfico medida, proporcionando, assim, a determinação do LL.

O expoente alométrico “b” foi determinado a partir da função logaritmica “ $\text{Log } y = \text{Log } a + b \text{ Log } x$ ” onde “y” é o $\text{VO}_{2\text{máxabs}}$ (em litros por minuto) e “x” é a massa corporal (em quilogramas). Foi calculado um expoente alométrico

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médio, para cada um dos grupos, utilizando as médias dos valores de $VO_{2m\acute{a}x}$ e massa corporal. Desta forma, foi obtida uma equação de reta com seu respectivo coeficiente de regressão.

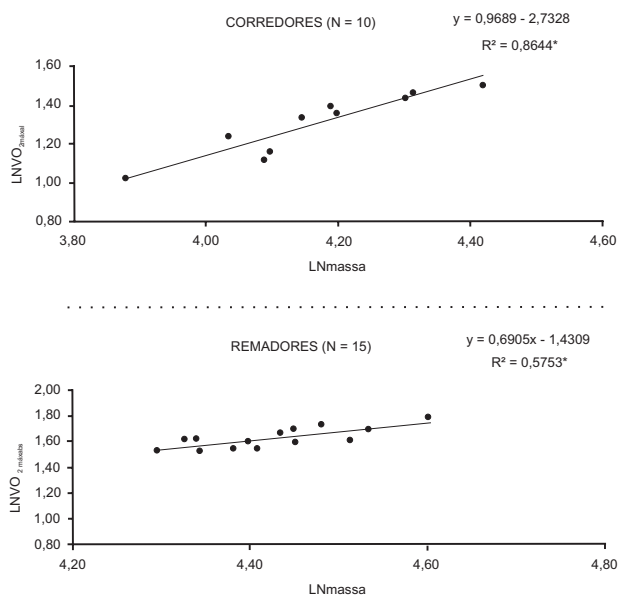
Foi utilizada a estatística descritiva, com média e desvio-padrão, para verificação das respostas de VO_2 absoluto e relativo à massa corporal total, ao expoente alométrico e à massa magra, nas situações de LA e máximo esforço, determinadas pelas respostas ventilatórias, para corredores e remadores e, somente na situação de LA, pela lactacidemia, para remadores. A normalidade e a homogeneidade dos dados foram analisadas através dos testes de Shapiro-Wilk e Levene. Foi utilizado, ainda, o teste *t-Student* para amostras independentes, com o objetivo de analisar os resultados do %G, do VO_{2la} e do $VO_{2m\acute{a}x}$, entre corredores e

remadores, comparando os resultados do VO_{2la} determinados pelas respostas ventilatórias e pela lactacidemia nos remadores. Foi realizada a correlação linear Produto Momento de Pearson, para verificação das relações sem causa-efeito entre os valores de VO_{2la} e o $VO_{2m\acute{a}x}$, determinados pelas respostas ventilatórias, para os corredores e remadores, e pela lactacidemia, apenas para os remadores, todos relativos às três formas de relativização. O índice de significância adotado foi de 0,05. Foi utilizado o pacote estatístico SPSS, versão 11.0.

RESULTADOS

Os corredores apresentaram um %G médio de 11,62, correspondente a uma média de massa magra de 57,5 kg. Os remadores apresentaram um %G médio de 13,68, correspondente a uma média de massa magra de 72,09 kg.

FIGURA 1
EQUAÇÕES DA RETA PARA CORREDORES E REMADORES, UTILIZADAS PARA A DETERMINAÇÃO DO EXPOENTE ALOMÉTRICO (COEFICIENTE ANGULAR) ATRAVÉS DO LOGARITMO NATURAL DO CONSUMO DE OXIGÊNIO ABSOLUTO PELO LOGARITMO NATURAL DA MASSA CORPORAL.



LNVO_{2maxabs} (l·min⁻¹) = Logaritmo Natural do Consumo de Oxigênio Absoluto

LNmassa (Kg) = Logaritmo Natural da Massa Corporal

* p < 0,05

Ambos os percentuais de gordura corporal apresentaram diferenças estatisticamente significativas. O expoente alométrico dos corredores foi de 0,9689 e dos remadores foi de 0,6905 (FIGURA 1).

Os valores médios do VO₂ absoluto e relativo à massa corporal total, ao expoente alométrico e à massa magra, de corredores e remadores, nas situações de máximo esforço e no LA, determinados pelas respostas

TABELA 2
MÉDIA E DESVIO-PADRÃO DO VO₂ ABSOLUTO E RELATIVO À MASSA CORPORAL TOTAL, AO EXPOENTE ALOMÉTRICO E À MASSA MAGRA DE CORREDORES E REMADORES NAS SITUAÇÕES DE MÁXIMO ESFORÇO E NO LA, DETERMINADOS PELAS RESPOSTAS VENTILATÓRIAS, E VO₂ ABSOLUTO E RELATIVO À MASSA CORPORAL TOTAL, AO EXPOENTE ALOMÉTRICO E À MASSA MAGRA DE REMADORES NO LA, DETERMINADOS PELA LACTACIDEMIA.

	CORREDORES (10)	REMADORES (15)
Respostas Ventilatórias		
VO _{2máx} (l.min ⁻¹)	3,72 ± 0,58	5,08 ± 0,40 ^a (p = 0,001)
VO _{2máx} (ml.kg ⁻¹ .min ⁻¹)	57,22 ± 3,37	60,97 ± 3,44 ^a (p = 0,685)
VO _{2máx} (ml.kg ^{-exp} .min ⁻¹)	65,13 ± 3,82	239,51 ± 11,98 ^a (p = 0,001)
VO _{2máx} (ml.kg ^{-mm} .min ⁻¹)	64,78 ± 4,30	70,63 ± 3,62 ^a (p = 0,001)
VO _{2La} (l.min ⁻¹)	3,47 ± 0,59 (93,3%)	4,38 ± 0,33 ^a (p = 0,018) (86,2%)
VO _{2La} (ml.kg ⁻¹ .min ⁻¹)	53,29 ± 4,20 (93,1%)	52,54 ± 2,96 ^b (p = 0,145) (86,2%)
VO _{2La} (ml.kg ^{-exp} .min ⁻¹)	60,66 ± 4,77	206,40 ± 10,34 ^a (p = 0,005)
VO _{2La} (ml.kg ^{-mm} .min ⁻¹)	60,33 ± 5,13	60,88 ± 3,3 ^b (p = 0,141)
Lactacidemia		
VO _{2La} (l.min ⁻¹)		3,34 ± 0,28 ^b (p = 0,016) (65,7%)
VO _{2La} (ml.kg ⁻¹ .min ⁻¹)		40,12 ± 2,22 ^b (p < 0,001) (65,8%)
VO _{2La} (ml.kg ^{-exp} .min ⁻¹)		157,62 ± 7,99 ^b (p < 0,001)
VO _{2La} (ml.kg ^{-mm} .min ⁻¹)		46,50 ± 2,80 ^b (p < 0,001)

Consumo máximo de oxigênio (VO_{2máx}), consumo de oxigênio no limiar anaeróbio (VO_{2La}), expoentes alométricos (exp) para corredores de 0,986 e remadores de 0,690; massa magra (mm) de cada sujeito. Valores percentuais referentes ao VO_{2máx}. (a) diferenças estatisticamente significativas, calculadas a partir do teste *t-Student* para amostras independentes, entre corredores e remadores; (b) diferenças estatisticamente significativas, calculadas a partir do teste *t-Student* para amostras dependentes, entre o consumo de oxigênio no limiar anaeróbio determinado pela ventilação e pela lactacidemia em remadores.

TABELA 3
CORRELAÇÃO ENTRE OS VALORES DE VO₂ RELATIVO À MASSA CORPORAL TOTAL, AO
EXPOENTE ALOMÉTRICO DO GRUPO E À MASSA MAGRA INDIVIDUAL, COM O VO_{2LA}
RELATIVO À MASSA CORPORAL TOTAL, AO EXPOENTE ALOMÉTRICO DO GRUPO E À
MASSA MAGRA INDIVIDUAL, DETERMINADOS PELAS RESPOSTAS VENTILATÓRIAS E PELA
LACTACIDEMIA.

	CORREDORES (10)	REMADORES (15)
VO _{2máx(ventilação)} (ml.kg ⁻¹ .min ⁻¹) - VO _{2La(ventilação)} (ml.kg ⁻¹ .min ⁻¹)	0,698*	0,641*
VO _{2máx(ventilação)} (ml.kg ^{-exp} .min ⁻¹) - VO _{2La(ventilação)} (ml.kg ^{-exp} .min ⁻¹)	0,696*	0,541*
VO _{2máx(ventilação)} (ml.kg ^{-mm} .min ⁻¹) - VO _{2La(ventilação)} (ml.kg ^{-mm} .min ⁻¹)	0,741*	0,603*
VO _{2máx(ventilação)} (ml.kg ⁻¹ .min ⁻¹) - VO _{2La(lactato)} (ml.kg ⁻¹ .min ⁻¹)		0,257
VO _{2máx(ventilação)} (ml.kg ^{-exp} .min ⁻¹) - VO _{2La(lactato)} (ml.kg ^{-exp} .min ⁻¹)		0,074
VO _{2máx(ventilação)} (ml.kg ^{-mm} .min ⁻¹) - VO _{2La(lactato)} (ml.kg ^{-mm} .min ⁻¹)		0,257

VO₂ determinado pelas respostas ventilatórias - VO_{2máx(ventilação)}
 VO_{2la} determinado pelas respostas ventilatórias - VO_{2la(ventilação)} e pela lactacidemia VO_{2la(lactato)}
 * p < 0,05

ventilatórias, bem como o VO₂ absoluto e relativo à massa corporal total, ao expoente alométrico e à massa magra de remadores no LA, determinado pela lactacidemia, são demonstrados na TABELA 2. Os resultados demonstraram um maior VO_{2máx} dos remadores, na forma absoluta e nas três formas relativas, determinados pelas respostas ventilatórias. Entretanto, não foram observadas diferenças significativas entre os grupos, quando o VO_{2máx} foi relativizado pela massa corporal total. Em relação ao VO_{2la}, determinado pelas respostas ventilatórias, foram observados maiores valores nos remadores, na forma absoluta e nas relativizações pelo expoente alométrico, com diferenças significativas, e na massa magra. Os valores relativos à massa corporal total foram maiores para os corredores.

Todos os valores de VO₂, absoluto e relativos, no LA, para os remadores, foram maiores e significativos, quando determinados pelas respostas ventilatórias em comparação com a lactacidemia.

Os deltas percentuais do VO₂ absoluto e relativo, no LA, determinados pelas respostas ventilatórias, foram maiores nos corredores em relação aos remadores. Nos remadores, os deltas percentuais do VO₂ absoluto e

relativo, no LA, foram maiores, quando determinados pelas respostas ventilatórias em comparação com a lactacidemia.

A TABELA 3 demonstra os resultados de correlação verificados entre os valores de VO_{2máx} relativo à massa corporal total, ao expoente alométrico e à massa magra, com o VO_{2la} relativo à massa corporal total, ao expoente alométrico e à massa magra, determinados pelas respostas ventilatórias e pela lactacidemia. Pode-se verificar que, independente da forma de relativização do VO₂ e do grupo analisado, todas as correlações foram boas (r > 0,5), quando determinadas pelas respostas ventilatórias. Entretanto, baixas correlações (r < 0,49) foram verificadas entre o VO_{2máx}, determinado pelas respostas ventilatórias, e o VO_{2la}, determinado pela lactacidemia, em todas as formas de relativização.

DISCUSSÃO

Apesar das diferenças metodológicas adotadas nos testes de consumo máximo de oxigênio, para cada uma das modalidades, e da determinação do limiar anaeróbio pela lactacidemia apenas nos remadores, os resultados verificados são passíveis de discussão devido a relevâncias fisiológicas.

A função logarítmica demonstrou um maior expoente alométrico no grupo dos corredores, em relação ao grupo dos remadores. Como consequência, os valores de $VO_{2máx}$ e VO_{2la} foram, significativamente, maiores nos remadores, em comparação com os corredores. Uma das principais justificativas para responder às diferenças nos expoentes alométricos, verificados em ambos os grupos, pode estar relacionada às diferenças significativas verificadas no %G dos corredores e remadores. Loftin et al. (2001), observando o comportamento do valor de pico do $VO_{2máx}$ em meninas obesas e não obesas, utilizando o método tradicional (relativização pela massa corporal total) e o alométrico (função logarítmica do $VO_{2máx}$ absoluto e da massa corporal total), encontraram, para as meninas não obesas, um expoente alométrico de 0,92 e, para as obesas, um expoente alométrico de 0,46, demonstrando uma diminuição do b, proporcional ao aumento do %G. Pelo método tradicional, os valores de capacidade aeróbia dos dois grupos eram similares. Entretanto, quando os valores da massa corporal foram corrigidos pelo método alométrico, houve uma diferença 50% menor no grupo de obesas, quando se observou o VO_2 relativo à massa. Tartaruga et al. (2007) destacam, também, a importância da superfície corporal no desenvolvimento de diferentes tarefas mecânicas, ou seja, na forma com que a massa corporal do sujeito (ou animal) é sustentada durante uma tarefa, bem como a resistência mecânica oferecida pelo meio onde a tarefa é desenvolvida, como variáveis que podem influenciar na determinação do expoente alométrico. Assim, uma outra possível justificativa para o menor b, encontrado para os remadores, além do %GC, seria a questão do deslocamento do peso corporal durante o exercício. O barco de remo permite um deslocamento mais fácil do peso corporal, devido à sua aerodinâmica, em comparação com a corrida em pista. Além disto, o remador apresenta uma menor área projetada, resultando em uma menor resistência ao avanço durante o seu deslocamento.

Os valores de $VO_{2máx}$, determinados pelas respostas ventilatórias, tanto na forma absoluta, como na forma relativa ao expoente alométrico e à massa magra, foram significativamente maiores nos remadores, em relação aos corredores. Da mesma forma, os valores de VO_{2la} foram maiores nos remadores, quando analisados na forma absoluta e relativa ao expoente alométrico. Estes resultados demonstram que a forma de expressar o $VO_{2máx}$ e o VO_{2la} pode influenciar, de forma significativa, nas relações de

performance entre-sujeitos. Chamari et al. (2005) coletaram os dados de $VO_{2máx}$ e de consumo submáximo de oxigênio ($VO_{2submáx}$) em jogadores de futebol, jovens e adultos, e determinaram um único expoente alométrico para os dois grupos com relação às duas variáveis. Para o $VO_{2máx}$, foi encontrado $b = 0,72$ e para o $VO_{2submáx}$, $b = 0,60$. Comparando os valores de VO_2 do método tradicional, com os valores obtidos após aplicação da escala alométrica, foram observadas diferenças. No método tradicional, o $VO_{2máx}$ dos adultos foi subestimado, não havendo diferença com relação aos jovens. Entretanto, ele foi 5% maior, quando relativizado a 72% da massa corporal. Já o $VO_{2submáx}$ dos jovens foi subestimado em 13%, quando analisado sob forma tradicional, não apresentando, porém, diferenças dos adultos, quando analisado sob o método alométrico. Em um estudo desenvolvido por Winter e Hamley (1976), analisando a influência da massa magra nos resultados de economia de corrida (ECO) de 32 corredores de rendimento, foram verificadas fortes correlações ($r > 0,6$) entre essas variáveis, em diferentes velocidades de corrida, demonstrando que, quanto maior a velocidade de corrida, maior a influência da massa magra nos valores de ECO.

De acordo com Bassett e Howley (2000), o $VO_{2máx}$ e o percentual do VO_{2la} em relação ao $VO_{2máx}$, influencia no comportamento da ECO e, conseqüentemente, no desempenho de corridas de meia e longas distâncias. A mesma análise pode ser feita para qualquer modalidade esportiva com predomínio aeróbio, como as provas de meio-fundo e fundo da natação, do ciclismo e do remo. Apesar dos resultados do presente estudo terem demonstrado um maior percentual do VO_{2la} em relação ao $VO_{2máx}$, dos corredores, independente da forma de expressão, não se pode afirmar que os corredores possuem um maior condicionamento físico do que os remadores, pois valores de $VO_{2máx}$ e VO_{2la} , relativos à massa corporal total, não foram diferentes entre ambos os grupos.

Analisando-se apenas os remadores, relacionando-se os valores absolutos e relativos do VO_{2la} , determinados pelas respostas ventilatórias e pela lactacidemia, foram verificadas baixas correlações ($r < 0,5$) entre ambas as formas de determinação do VO_{2la} , demonstrando que o método de determinação do VO_{2la} pode influenciar nos resultados de VO_2 e, conseqüentemente, nas relações entre $VO_{2máx}$ e VO_{2la} . Okano et al. (2006), relacionando o

LA, determinado pelo equivalente ventilatório de dióxido de carbono e pelas respostas de lactato sangüíneo, em oito ciclistas, demonstraram uma forte correlação ($r=0,90$) entre os valores de VO_{2la} determinados pelos dois métodos. Da mesma forma, os trabalhos de Wasserman et al. (1973) demonstraram que os níveis de lactato apresentam uma forte correlação com a ventilação, em função do tamponamento dos íons hidrogênio (H^+) pelo íon bicarbonato (HCO_3^-), e a subsequente eliminação na forma de dióxido de carbono (CO_2) pela respiração ($H^+ + HCO_3^- \leftrightarrow H_2CO_3 \leftrightarrow CO_2 + H_2O$).

As diferenças do presente estudo, em relação ao estudo de Okano et al. (2006), estão na metodologia adotada para a determinação do VO_{2la} . No estudo aqui relatado, o LA ventilatório foi determinado pela curva de ventilação e pelo equivalente ventilatório de dióxido de carbono. Já o LA lactacidêmico foi determinado pelo método $D_{máx}$, diferentemente do método utilizado por Okano et al. (2006), no qual foi utilizado o ponto de inflexão da curva lactato vs potência. Baptista et al. (2005) destacam que os métodos de determinação do VO_{2la} , através da lactacidemia, podem superestimar os resultados, sugerindo-se, conforme Stegmann et al. (1981), a utilização de um limiar anaeróbio individual. Este método, desenvolvido por pesquisadores da Alemanha, baseia-se na habilidade individual do atleta de manter um estado estável de lactato, durante um exercício prolongado. De fato, em um estudo subsequente, realizado por McLellan e Jacobs (1993), a intensidade de exercício, correspondente ao LA individual, mostrou ser a maior potência que pode ser mantida pelos atletas por um

período de exercício entre 15 a 20 minutos, sem um aumento no acúmulo de lactato sangüíneo, e é, por isso, também, chamado por alguns grupos de pesquisa como sendo o máximo estado estável de lactato ou, como muitas vezes é expresso na língua inglesa, pela sigla MLSS (*Maximal Lactate Steady State*) (Baptista et al., 2005).

Por fim, foi verificado que, independente da forma de expressão do $VO_{2máx}$ e do VO_{2la} , ambos determinados pelas variáveis ventilatórias, a relação foi boa. De acordo com Weltman e Katch (1979), a predição do $VO_{2máx}$, pelo LA, pode ser de até 89% para sujeitos bem condicionados, destacando que a referida relação deve ser analisada do ponto de vista da acidose metabólica e não do metabolismo causado pela hipoxia. Essa afirmação corrobora com os achados de Davis et al. (1976), onde os autores verificaram uma forte correlação entre o LA, determinado pelas variáveis ventilatórias e pela lactacidemia, correspondente a $r=0,95$. Além disso, Cotes et al. (1969) e Jones e Pearson (1969) verificaram existir relação entre $VO_{2máx}$ e $VO_{2submáx}$ com parâmetros antropométricos e, conseqüentemente, relação entre $VO_{2máx}$ e $VO_{2submáx}$.

CONCLUSÃO

Com base nos resultados encontrados neste estudo, pode-se concluir que a forma de relativização do VO_2 não influencia na relação entre VO_{2la} e $VO_{2máx}$ em corredores e remadores de rendimento. No entanto, a forma de determinação do VO_2 pode ser uma variável interveniente na relação entre VO_{2la} e $VO_{2máx}$.

REFERÊNCIAS BIBLIOGRÁFICAS

- BAPTISTA RR, OLIVEIRA LGD, FIGUEIREDO GBD, CONTIERI JR, LOSS JFE, OLIVEIRA ARD. Limiar de Lactato em Remadores: Comparação entre Dois Métodos de Determinação. Revista Brasileira de Medicina do Esporte 2005; 11(4):247-50.
- BASSETT DR, HOWLEY ET. Limiting Factors For Maximum Oxygen Uptake and Determinants of Endurance Performance. Medicine and Science in Sport and Exercise 2000; 32(1):70-84.
- BERGH U, SJODIN B, FORSBERG A, SVEDENHAG J. The Relationship Between Body Mass and Oxygen Uptake During Running in Humans. Medicine and Science in Sport and Exercise 1991; 23(2):205-11.
- BRISWALTER J, LEGROS P, DURAND M. Running Economy, Preferred Step Length Correlated to Body Dimensions in Elite Middle Distance Runners. The Journal of Sports Medicine and Physical Fitness 1996; 36(1):7-15.
- CHAMARI K, MOUSSA-CHAMARI I, BOUSSAIDI L, HACHANA Y, KAOUECH F, WISLOFF U. Appropriate Interpretation of Aerobic Capacity: Allometric Scaling in Adult and Young Soccer Players. British Journal of Sports Medicine 2005; 39(2): 97-101.

- CHENG B, KUIPERS H, SNYDER AC, KEIZER HA, JEUKENDRUP A, HESSELINK M. A New Approach for the Determination of Ventilatory and Lactate Thresholds. *International Journal of Sports Medicine* 1992; 13(7):518-22.
- CONLEY DL, KRAHENBUHL GS. Running Economy and Distance Running Performance of Highly Trained Athletes. *Medicine and Science in Sport and Exercise* 1980; 12(5):357-60.
- COSTILL DL. Physiology of Marathon Running. *Jama* 1972; 221(9):1024-9.
- COTES JE, DAVIES CT, EDHOLM OG, HEALY MJ, TANNER JM. Factors Relating to the Aerobic Capacity of 46 Healthy British Males and Females, Ages 18 To 28 Years. *Proceedings of the Royal Society of London* 1996; 174(34):91-114.
- DANIELS J, DANIELS N. Running Economy of Elite Male and Elite Female Runners. *Medicine and Science in Sport and Exercise* 1992; 24(4):483-9.
- DARVEAU CA, SUAREZ RK, ANDREWS RD, HOCHACHKA PW. Allometric Cascade as a Unifying Principle of Body Mass Effects on Metabolism. *Nature* 2002; 417(6885):166-70.
- DAVIS JA, VODAK P, WILMORE JH, VODAK J, KURTZ P. Anaerobic Threshold and Maximal Aerobic Power for Three Modes of Exercise. *Journal of Applied Physiology* 1976; 41(4):544-50.
- DENADAI BS. Consumo Máximo de Oxigênio: Fatores Determinantes e Limitantes. *Revista Brasileira de Atividade Física e Saúde* 1995; 1(1):85-94.
- DENIS C, FOUQUET R, POTY P, GEYSSANT A, LACOUR JR. Effect of 40 weeks of Endurance Training on the Anaerobic Threshold. *International Journal of Sports Medicine* 1982; 3(4):208-14.
- FARRELL PA, WILMORE JH, COYLE EF, BILLING JE, COSTILL DL. Plasma Lactate Accumulation and Distance Running Performance. *Medicine and Science in Sports* 1979; 11(4):338-44.
- FORSYTH JJ, FARRALLY MR. A Comparison of Lactate Concentration in Plasma Collected from the Toe, Ear and Fingertip after a Simulated Rowing Exercise. *British Journal of Sports Medicine* 2000; 34(1):35-8.
- HOWLEY ET, BASSETT DR JR, WELCH HG. Criteria for Maximal Oxygen Uptake: Review And Commentary. *Medicine and Science in Sport and Exercise* 1995; 27(9):1292-301.
- HIS WL., LAN C, LAI JS. Normal Standards For Cardiopulmonary Responses To Exercise Using A Cycle Ergometer Test. *Journal of the Formosan Medical Association* 1998; 97(5):315-22.
- JACKSON AS, POLLOCK ML. Generalized Equations for Predicting Body Density of Men. *The British Journal of Nutrition* 1978; 40(3):497-504.
- JENSEN K, JOHANSEN L, SECHER NH. Influence of Body Mass on Maximal Oxygen Uptake: Effect of Sample Size. *European Journal of Applied Physiology* 2001; 84(3):201-5.
- JONES PR, PEARSON J. Anthropometric Determination of Leg Fat and Muscle Plus Bone Volumes in Young Male and Female Adults. *The Journal of Physiology* 1969; 204(2):63-6P.
- KUMAGAI S, TANAKA K, MATSUURA Y, MATSUZAKA A, HIRAKOBA K, ASANO K. Relationships of the Anaerobic Threshold with the 5 Km, 10 Km, and 10 Mile Races. *European Journal of Applied Physiology and Occupational Physiology* 1982; 49(1):13-23.
- KYROLAINEN H, BELLI A, KOMI PV. Biomechanical Factors Affecting Running Economy. *Medicine and Science in Sport and Exercise*, 2001; 33(8):1330-7.
- LOFTIN M, SOTHERN M, TROSCLAIR L, O'HANLON A, MILLERJ, UDALL J. Scaling VO(2) Peak in Obese and Non-Obese Girls. *Obesity Research* 2001; 9(5):290-6.

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MCLELLAN TM, JACOBS I. Reliability, Reproducibility and Validity of the Individual Anaerobic Threshold. *European Journal of Applied Physiology and Occupational Physiology* 1993; 67(2):125-31.

MEYER T, WELTER JP, SCHARHAG J, KINDERMANN W. Maximal Oxygen Uptake During Field Running Does Not Exceed that Measured During Treadmill Exercise. *European Journal of Applied Physiology* 2003; 88(4-5):387-9.

NICHOLSON RM, SLEIVERT GG. Indices of Lactate Threshold and their Relationship with 10-Km Running Velocity. *Medicine and Science in Sport and Exercise* 2001; 33(2):339-42.

NOVACHEK TF. The Biomechanics of Running. *Gait Posture* 1998; 7(1):77-95.

NUMMELA AT, PAAVOLAINEN LM, SHARWOOD KA., LAMBERT MI, NOAKESTD, RUSKO HK. Neuromuscular Factors Determining 5 Km Running Performance and Running Economy in Well-Trained Athletes. *European Journal of Applied Physiology* 2006; 97(1):1-8.

OKANO AH, ALTIMARI LR, SIMÕES HG, MORAES ACD, NAKAMURA FY, CYRINO ES, BURINI RC. Comparação entre Limiar Anaeróbio Determinado por Variáveis Ventilatórias e pela Resposta do Lactato Sangüíneo em Ciclistas. *Revista Brasileira de Medicina do Esporte* 2006;12(1):39-44.

PETROSKI EL. Desenvolvimento e Validação de Equações Generalizadas para Predição da Densidade Corporal. Santa Maria, RS: Programa de Pós-graduação da Escola de Educação Física, Universidade Federal de Santa Maria, 1995.

POWERS SK, DODD S, DEASONR, BYRD R, MCKNIGHT T. Ventilatory Threshold, Running Economy and Distance Running Performance of Trained Athletes. *Research Quarterly for Exercise and Sport* 1983; 54(2):179-82.

SALTIN B, ASTRAND PO. Maximal Oxygen Uptake in Athletes. *Journal of Applied Physiology* 1967; 23(3):353-8.

SILVA AEL, OLIVEIRA FRD. Consumo de Oxigênio durante o Exercício Físico: Aspectos Temporais e Ajustes de Curvas. *Revista Brasileira de Cineantropometria e Desenvolvimento Humano* 2004; 6(2):73-82.

SIRI WE. *Body Composition from Fluid Spaces and Density*. Washington, USA: National Academy of Science (Techniques for measuring body composition), 1961.

SJODIN B, SVEDENHAG J. Applied Physiology of Marathon Running. *Sports Medicine* 1985; 2(2):83-99.

STEGMANN H, KINDERMANN W, SCHNABEL A. Lactate Kinetics and Individual Anaerobic Threshold. *International Journal of Sports Medicine* 1981; 2(3):160-5.

SVEDENHAG J. Maximal and Submaximal Oxygen Uptake during Running: How Should Body Mass Be Accounted for? *Scandinavian Journal of Medicine & Science in Sports* 1995;5(4):175-80.

SVEDENHAG J, SJODIN B. Body-Mass-Modified Running Economy and Step Length in Elite Male Middle and Long-Distance Runners. *International Journal of Sports Medicine* 1994; 15(6):305-10.

TARTARUGA LAP, COERTJENS M, TARTARUGA MP, MEDEIROS MHD, KRUEL LFM. Influence of the Allometric Scale on the Relationship Running Economy and Biomechanical Variables in Runners. *Medicine and Science in Sport and Exercise* 2007; 39(5):S208-S209.

TARTARUGA LAP, TARTARUGA MP, RIBEIRO JL, COERTJENS M, RIBAS LR, KRUEL LFM. Correlação entre Economia de Corrida e Variáveis Cinemáticas em Corredores de Alto Nível. *Revista Brasileira de Biomecânica* 2004; 5(9):51-8.

VANDEBURGH PM, DOOMAN C. Considering Body Mass Differences, Who Are the World's Strongest Women? *Medicine and Science in Sport and Exercise* 2000;32(1):197-201.

WASSERMAN K, WHIPP BJ, KOYL SN, BEAVER WL. Anaerobic Threshold and Respiratory Gas Exchange During Exercise. *Journal of Applied Physiology* 1973; 35(2):236-43.

WELTMAN A, KATCH VL. Relationship between the Onset of Metabolic Acidosis (Anaerobic Threshold) and Maximal Oxygen Uptake. The Journal of Sports Medicine and Physical Fitness 1979; 19(2):135-42.

WEST GB, BROWN JH, ENQUIST BJ. A General Model for the Origin of Allometric Scaling Laws in Biology. Science 1997; 276(5309):122-6.

WINTER, EM, HAMLEY EJ. Sub Maximal Oxygen Uptake Related to Fat Free Mass and Lean Leg Volume in Trained Runners. British Journal of Sports Medicine 1976; 10(4):223-5.

YOSHIDA T, CHIDA M, ICHIOKA M, SUDA Y. Blood Lactate Parameters Related to Aerobic Capacity and Endurance Performance. European Journal of Applied Physiology and Occupational Physiology 1987; 56(1):7-11.

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