This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

The anthropometry of economical running

PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1249/MSS.0000000000002158>

PUBLISHER

Lippincott, Williams & Wilkins

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This is a non-final version of an article published in final form in Black, M.I. ... et al, 2019. The anthropometry of economical running. *Medicine and Science in Sports and Exercise*, 52(3), pp. 762-770. The definitive published version is available at <https://doi.org/10.1249/MSS.0000000000002158>.

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Black, Matthew I, Sam Allen, Steph Forrester, and Jonathan Folland. 2019. "The Anthropometry of Economical Running". Loughborough University. <https://hdl.handle.net/2134/9923819.v1>.

The anthropometry of economical running

Original Investigation

Matthew I. Black^{1,3}, Sam J. Allen¹, Steph E. Forrester², and Jonathan P. Folland¹

¹School of Sport, Exercise and Health Sciences, Loughborough University, Leicestershire, LE11 3TU, United Kingdom.

²Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Leicestershire, LE11 3TU, United Kingdom.

³School of Sport and Health Sciences, College of Life and Environmental Sciences, University of Exeter, St. Luke's Campus, Heavitree Road, Exeter, EX1 2LU, United Kingdom.

Address for Correspondence:

Jonathan P. Folland, Ph.D

School of Sport, Exercise and Health Sciences, Loughborough University, Leicestershire, LE11 3TU, United Kingdom.

Tel: +44 (0)1509 226 334

E-mail: J.P.Folland@lboro.ac.uk

Abstract word count: 266

Text-only word count: 5013

Number of figures and tables: 2 Figure, 4 Tables

Abstract

The influence of anthropometry and body composition on running economy is unclear, with previous investigations involving small relatively homogeneous groups of runners and limited anthropometric/composition measurements. **Purpose:** To comprehensively investigate the relationships of anthropometry and body composition with running economy within a large heterogeneous sample of runners. **Methods:** Eighty-five runners (Males (M), $n=45$; Females (F) $n=40$), of diverse competitive standard, performed a discontinuous protocol of incremental treadmill running (4 min stages, $1 \text{ km} \cdot \text{h}^{-1}$ increments) to establish locomotory energy cost (LEc) of running at submaximal speeds (averaged across $10\text{-}12 \text{ km} \cdot \text{h}^{-1}$; the highest common speed < lactate turnpoint). Measurements of anthropometry, including segment lengths, perimeters, masses and moments of inertia (MoI), and body composition were obtained using tape-based measurements and dual-energy x-ray absorptiometry (DXA). **Results:** Absolute LEc (ABSLEc , $\text{kcal} \cdot \text{km}^{-1}$) was positively correlated with 21 (out of 27) absolute anthropometric variables in both male and female cohorts. Multiple regression analysis revealed that one variable (mean perimeter z-score) explained 49.4% (M) and 68.9% (F) of the variance in ABSLEc . Relative LEc (RELLEc , $\text{kcal} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$) was also correlated with 5 (M) and 7 (F) normalised anthropometric variables, and regression analysis explained 31.6% (M; percentage bone mass and normalised hip perimeter) and 33.3% (F, normalised forearm perimeter) of the variance in RELLEc . **Conclusions:** These findings provide novel and robust evidence that anthropometry and body composition variables, predominantly indicative of relative slenderness, explain a considerable proportion of the variance in running economy (i.e., more slender, lower energy cost). We therefore recommend that runners and coaches are attentive to relative slenderness in selecting and training athletes with the aim of enhancing running economy, and improving distance running performance.

Key Words: BMI, slenderness, DXA, running economy, locomotory energy cost

INTRODUCTION

Running economy is defined as the energy/oxygen cost of running a given distance at a submaximal speed (1, 2). Running economy is known to be an important determinant of long-distance (>1500-m) running performance (3, 4) and to vary widely between runners (>30%; [5, 6]). Many factors are thought to influence running economy and can be broadly categorised as physiological, biomechanical and anthropometrical (see 7-9 for reviews). Given the fundamental contribution of running economy to long-distance running performance, determining the specific anthropometric and body composition factors that are most important for economical movement has great practical relevance.

It is well known that, all other things being equal, absolute energy cost increases with increased body size and, specifically, body mass, such that greater body mass is directly associated with higher absolute energy cost (2), and a proportional linear relationship has been documented in trained runners (1). Nonetheless the extent to which body mass and/or other indices of body size (e.g., height), explain the differences in absolute energy cost between runners has not been documented and may inform the determinants of absolute energy cost. The influence of body mass on absolute energy cost could purely reflect differences in body size but may also reflect differences in body composition (i.e., increased fat, bone, and/or lean (i.e. non-fat and non-bone mass), however the relationship between body composition and the absolute energy cost of runners has not been established.

Moreover, running economy is typically expressed relative to body mass, and in runners ratio scaling (e.g., $\text{kcal.kg}^{-1}.\text{km}^{-1}$) has been found to effectively remove any influence of body mass (1). Thus relative energy cost, that facilitates body-mass-independent inter-individual comparisons, and is not confounded by differences in substrate metabolism (1, 10), is perhaps the best, widely used measure of running economy. However the influence of other indices of body size (e.g., height, BMI) or relative measures of body composition and anthropometry (e.g.,

segmental mass, inertia, perimeters and lengths) on relative energy cost has been largely unexplored.

Running requires the repetitive forward and backward movement of the legs. Theoretically the energy cost of these movements is largely related to the transverse moments of inertia (MoI) of the legs and their constituent segments (i.e., the foot, shank/calf, and thigh) which must be overcome to accelerate each limb back and forth. Indeed, indirect support for this notion is provided by “weight loading” studies which have shown that the addition of mass can predictably impair running economy and performance (3), and carrying this mass at the distal aspect of a segment is more energetically expensive than carrying the same load positioned more proximally (11). Further indirect evidence to support MoI as an important determinant of running economy is provided by observations that faster long-distance runners, who are known to be more economical (6, 12), typically possess slimmer limbs and more slender body types than slower long-distance runners (13-17). Furthermore, proportionately smaller limb perimeters, and presumably a lower limb mass and MoI, are thought to be important factors in the superior running economy of Kenyan athletes relative to their Caucasian counterparts (18, 19). However, aside from interventions that have added mass, and indirect evidence, the relationship between biological segmental mass/inertia and absolute and relative running economy has not been investigated.

In addition to segment mass, limb MoI is also dependent upon segment length and the distribution of mass along the segment. It is therefore possible that segment length, via its relationship with segment MoI, may also be associated with running economy. Whilst leg and segment lengths have been positively related to running performance (20) the relationship with running economy has been poorly documented.

Given the potential influence of anthropometry and body composition on running economy, and the paucity of data, a rigorous investigation involving a large heterogeneous sample of runners is warranted. The purpose of the present study was to determine the relationship of absolute body size (mass, height, BMI, segment mass, perimeter, length and MoI) and composition (fat, bone and lean mass) with absolute running economy ($\text{kcal}\cdot\text{km}^{-1}$), as a preliminary step to investigating the relationship between relative anthropometry (segment mass, perimeter, length and MoI) and body composition (percentage fat, bone and lean tissue) with relative energy cost of running ($\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$). Given the known differences between males and females in anthropometry and body composition (1, 21), these groups were assessed separately.

METHODS

Participants

Eight-five healthy long-distance runners, including male (M, $n = 45$, Age 28 ± 7 y) and female (F, $n = 40$, Age 28 ± 7 y) cohorts, volunteered and provided written informed consent to participate in this study, which had been approved by the National Research Ethics Service and the Loughborough University Ethics Committee. All participants were regular runners (Training Distance 37 ± 23 , range 5 to 110 miles $\cdot\text{wk}^{-1}$; Frequency 5 ± 2 , range 2 to 12 sessions $\cdot\text{wk}^{-1}$) who considered running to be their primary sport or physical activity and had a BMI $<24 \text{ kg}\cdot\text{m}^{-2}$. Participants were free from moderate/serious (previous 3 months) or minor (previous 1 month) musculoskeletal injury. A large heterogeneous group of runners, with a diverse performance standard were recruited. Their best running performance in the previous 12 months for distances between 1500 m and the marathon in UK Athletics sanctioned track and road races was recorded and corroborated by reference to actual race results. All times

were converted to an equivalent 10-km road time using IAAF points scores (22), and are expressed as a percentage of the current 10-km road World Record times (M, 26 min 44 s; F, 30 min 21 s). Descriptive performance and physiology data for the cohort are presented in Table 1.

Experimental Overview

Participants visited the laboratory on two occasions separated by ≤ 14 days, to perform a treadmill familiarisation and an experimental session. Participants were instructed to report to the laboratory in a well-hydrated, rested state, having completed no strenuous exercise within the previous 36 h, and having abstained from alcohol, and caffeine for the preceding 24 h, and 6 h, respectively. During the first session, participants performed a treadmill familiarisation run; extensively practicing lowering themselves onto, and lifting themselves clear of, the moving treadmill belt whilst wearing the mask required for respiratory measurements. The second session began with assessment of anthropometry and body composition using tape-based measures and dual-energy x-ray absorptiometry (DXA). This was followed by an incremental treadmill test; a submaximal discontinuous incremental protocol of 4-min stages, immediately followed by a continuous protocol performed to volitional exhaustion with respiratory gas and blood lactate measurements. All experimental visits were conducted in the morning (0730-1200), and laboratory conditions were similar for all participants (temperature, 18-20°C; relative humidity, 45-55%). During both visits, all participants were required to wear the same neutral racing flat shoes (New Balance® RC 1400 v2).

Anthropometry and body composition

Participants wore minimal clothing (running shorts and vest) and were instructed to remove any metal objects prior to assessment. Body mass was assessed using digital scales (Seca 700;

Hamburg, Germany) and was recorded to the nearest 0.1 kg, and height was measured to the nearest 0.1 cm (Harpenden Stadiometer, Holtain Limited, UK). Forty-five whole-body segmental anthropometric measurements, including eight segment perimeters of particular interest, were obtained from each participant according to a reduced set inertia model (23). Tape based measurements of segment perimeters were made whilst the participant stood in a modified anatomical reference position, with the palms of their hands rested against the side of their body and included: mid-thigh perimeter (at 50% of the distance between the greater trochanter and knee joint space), waist at the level of the umbilicus, chest at nipple level, and the maximum perimeters of the calf, forearm, upper arm and hips. All the anthropometric measurements were determined by the same trained assessor, were recorded to the nearest 0.1 cm, and performed twice. A third measurement was made when the difference between the two measures was greater than 0.5 cm and the mean used for further analyses. Measurements were made on both the left and right limbs, and the mean used for all further analyses. As a single overall index of segment perimeters, specific segment perimeters were converted into a z-score (difference in standard deviations of each participant from the mean) before averaging the eight perimeter z-scores to calculate a mean of perimeter z-scores. The set of 45 anthropometric measurements was used for the determination of segmental transverse moments of inertia about the centre of mass of the segment (MoI; Inertia, Visual 3D; C-Motion, Germantown, MD), with the foot, calf and thigh of particular relevance to the current study.

Whole-body composition (bone mass; fat mass; lean mass, i.e., non-fat and non-bone mass) and segmental mass (foot, calf, thigh, and arm) and length (calf, thigh, and leg) were determined via DXA (Lunar iDXA; GE Healthcare, Madison, WI, USA). All scans were performed by the same trained operator in accordance with standardised testing protocols. The DXA scanner was calibrated daily, with a minimum of 3 daily calibrations prior to any body composition assessment. From the frontal plane DXA image the length of the calf and thigh

were determined by assessment of the distance between the superior of the lateral tibial condyle and inferior of the lateral tibial malleolus, and the distance between the inferior of the lateral femoral condyle and the superior head of the femur, respectively. Leg segment length was determined by assessment of the distance between the superior of the head of the femur and the inferior of the calcaneus. Foot length was measured with a Brannock device. From the frontal plane DXA image, segment mass was assessed by carefully drawing a customised area around the segment of interest. Briefly, the boundaries between the foot, calf and thigh segments were defined as: the inferior articular surface of the tibia and the lateral and medial malleoli; the tibiofemoral joint space; and the outline above the greater trochanter, femoral neck and below the ischium. An overall leg mass was determined by the summation of foot, calf and thigh segment masses. In addition to assessment of absolute values, measurements of whole-body composition and segmental mass were normalised to whole-body mass, and measurements of length and perimeter were normalised to standing height, and moments of inertia were normalised to the product of body mass and the square of standing height.

Submaximal and maximal running assessment

Participants performed a discontinuous submaximal incremental test for the determination of the energy cost of running, lactate turnpoint (LTP) and $\dot{V}O_{2\max}$. The test started at 7 km.h⁻¹ for females, and 8 km.h⁻¹ for males, and consisted of 4-min stages of running, interspersed by 30-s rest periods, during which the subject straddled the moving treadmill belt whilst ~30 μ L fingertip capillary blood sample was obtained for analysis of blood lactate (YSI 2300, Yellow Springs Instruments, Yellow Springs, OH). Increments (+1 km.h⁻¹). This protocol continued until blood lactate (BLa) had risen >2 mmol.L⁻¹ from the previous stage (LTP), at which point the participant started the continuous maximal running assessment (i.e. no rest periods) with the treadmill speed increased by 1 km.h⁻¹ every 2 min until volitional exhaustion.

173

174 *Pulmonary gas exchange*

175 Breath-by-breath pulmonary gas exchange data were measured continuously throughout the
176 running assessment. Participants wore a low-dead space mask and breathed through a turbine
177 assembly (Jaeger Triple V, Jaeger GmbH, Hoechberg, Germany). The inspired and expired gas
178 volume and concentration signals were continuously sampled, the latter using electrochemical
179 (O_2) and infrared (CO_2) analysers (Jaeger Vyntus CPX, Carefusion, San Diego, CA) via a
180 capillary line. These analysers were calibrated before each test using a known gas mixture (16%
181 O_2 and 5% CO_2) and ambient air. The turbine volume transducer was calibrated using a 3-L
182 syringe (Hans Rudolph, KS). The volume and concentration signals were time-aligned,
183 accounting for the transit delay in capillary gas and analyser rise time relative to the volume
184 signal. Breath-by-breath $\dot{V}O_2$ data were initially examined to exclude errant breaths caused by
185 coughing, swallowing etc., and those values lying more than 4 SDs from the local mean were
186 removed. Subsequently, the breath-by-breath data were converted to second-by-second data
187 using linear interpolation. $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and RER were quantified for the final 60 s of each
188 stage of the submaximal protocol. $\dot{V}O_{2max}$ was determined as the highest 30-s moving average.

189

190 ***Data Analysis***

191 *Calculation of the energy cost of running*

192 The 60-s average $\dot{V}O_2$ and $\dot{V}CO_2$ data collected during the final minute of each submaximal
193 (<LTP; RER <1.00) stage were used to calculate the energy cost of running. Updated
194 non-protein respiratory quotient equations (24) were used to estimate substrate utilisation
195 ($g \cdot min^{-1}$). The energy derived from each substrate was calculated by multiplying fat and
196 carbohydrate utilisation by 9.75 kcal and 4.07 kcal, respectively (25). Energy expenditure at
197 rest during quiet standing was subtracted from the energy cost of running to provide the

locomotory energy cost (LEc) and was subsequently expressed in absolute ($_{\text{ABS}}\text{LEc}$; $\text{kcal}\cdot\text{km}^{-1}$) and relative ($_{\text{REL}}\text{LEc}$; $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) terms. LEc was averaged over the three highest speeds at which all participants remained below their LTP (10-12 $\text{km}\cdot\text{h}^{-1}$).

Statistical Analysis

The male and female cohorts were assessed separately. The bivariate relationships between $_{\text{ABS}}\text{LEc}$ ($\text{kcal}\cdot\text{km}^{-1}$) and anthropometric and body composition parameters were assessed using independent Pearson's product moment correlation coefficient. P values were corrected for multiple tests using the Benjamini-Hochberg procedure (26) with a false detection rate of 5% and significance defined as $P\leq 0.05$. Variables significantly correlated with running economy were subsequently included in a stepwise multiple linear regression (MLR) analysis to calculate the total variance explained by the best combination of predictors. For inclusion in the regression model, each additional variable had to significantly increase the explained variance (Adjusted R^2 , $P<0.05$). Variables were excluded if the variance inflation factor >2.5 ; thus, the reported models all had a variance inflation factor <2.5 . The statistical analyses described above were repeated to understand the relationships between relative measures of anthropometry, body composition, segment inertia, and $_{\text{REL}}\text{LEc}$ ($\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$). All statistical analysis procedures were performed with IBM SPSS Statistics Version 22 (IBM Corp., New York, NY, USA). Data are presented as mean $\pm$ SD, and between participant variability was assessed by calculating between participant coefficient of variation ($\text{CVb} = 100 \times \text{SD}/\text{mean}$).

RESULTS

Absolute locomotory energy cost was $54.3 \pm 9.1 \text{ kcal}\cdot\text{km}^{-1}$ ($\text{CVb } 16.7\%$) for males and $44.6 \pm 7.6 \text{ kcal}\cdot\text{km}^{-1}$ (17.0%) for females (Table 1). Relative locomotory energy cost for males was $0.79 \pm 0.10 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$ ($\text{CVb } 12.7\%$) and females $0.79 \pm 0.09 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$ (11.4%).

223 Anthropometric and body composition values of the participants are provided in Table 2.
224 Variability of the anthropometric and body composition factors was itself quite variable (CVb:
225 M absolute 3.5-20.6%, normalised 2.5-28.3%; F absolute 4.3-26.7%, normalised 2.4-20.0%).
226 Height and segment lengths showed relatively limited variability (M & F, absolute &
227 normalised CVb 2.5-6.6%), as did segment perimeters (3.7-8.6%). Segment masses (M & F,
228 absolute CVb 10.0-15.4% and normalised 3.6-14.7%) and MoIs (absolute 17.8 – 32.2%;
229 normalised 7.0-21.3%) were somewhat more variable. Fat mass (M & F, absolute & normalised
230 CVb 20.0-31.6) showed greater variability than lean and bone mass (4.6-12.2%).

231

232 *Predictors of absolute locomotory energy cost ($\text{kcal}\cdot\text{km}^{-1}$)*

233 A total of twenty-one out of 27 measures of anthropometry and body composition were
234 correlated with ABSLEc in both the male and female cohorts, this included 20 specific variables
235 that were correlated in both cohorts and a further two variables showing sex dimorphic
236 relationships; bone mass (F only) and foot MoI (M only; $P\leq 0.05$; Table 3). Body mass and
237 BMI showed strong positive correlations with ABSLEc in both sexes (body mass, $r=0.661$ (M),
238 $r=0.754$ (F); BMI, $r=0.610$ (M), $r=0.716$ (F); all $P<0.001$), but there were no relationships with
239 height or segment lengths. However, all eight individual segment perimeters (M, $r=0.432$ - 0.699 ,
240 $P\leq 0.004$; F, $r=0.534$ - 0.805 , $P<0.001$) and all five segment masses (M, $r=0.331$ - 0.644 , $P\leq 0.035$;
241 F, $r=0.357$ - 0.784 , $P\leq 0.031$) were correlated with ABSLEc in M and F. The highest correlations
242 with ABSLEc in both cohorts were for the mean of perimeter z-scores (M, $r=0.711$; F, $r=0.835$;
243 both $P\leq 0.001$; Figure 1 A & B). In terms of body composition, greater absolute lean mass (M,
244 $r=0.488$; F, $r=0.655$; both $P\leq 0.001$) and fat mass (M, $r=0.478$; F, $r=0.503$; both $P\leq 0.002$) were
245 associated with ABSLEc in both sexes, but a correlation with bone mass was only found in F
246 ($r=0.549$; $P<0.001$), not M. MoI for the thigh (M, $r=0.585$; F, $r=0.574$; both $P<0.001$), calf (M,

$r=0.556$; F, $r=0.514$; both $P \leq 0.001$) and the foot in M ($r=0.322$, $P=0.040$), but not in F were also positively correlated with $_{ABS}LEc$.

Stepwise multiple linear regression (MLR) analyses inputting all the absolute predictor variables significantly correlated with $_{ABS}LEc$ revealed that only one variable contributed to the explained variance in $_{ABS}LEc$ in both cohorts, with mean perimeter z-score (X_1) explaining 49.4% (M, Figure 2A) and 68.9% (F, Figure 2B) of the variance, which can be predicted using equations 1 and 2 respectively:

$$\text{Males: } _{ABS}LEc \text{ (kcal.km}^{-1}\text{)} = (8.573 * X_1) + 54.296 \quad (1)$$

$$\text{Females: } _{ABS}LEc \text{ (kcal.km}^{-1}\text{)} = (7.847 * X_1) + 44.643 \quad (2)$$

Predictors of relative locomotory energy cost (kcal·kg⁻¹·km⁻¹)

A much smaller number of normalised anthropometric and body composition variables were associated with relative locomotory energy cost ($_{REL}LEc$); five variables in M and seven in females (Table 4). In F only normalised segment perimeters were correlated with $_{REL}LEc$, and normalised perimeters accounted for three of the five associations in M. $_{REL}LEc$ was not related to body mass or height in M or F, and therefore confirmed that the normalisation effectively removed the influence of body mass on $_{REL}LEc$. Nonetheless BMI was positively related to $_{REL}LEc$ in M i.e., a greater BMI was associated with higher energy cost per kilogram of mass ($r=0.376$; $P=0.049$), with a similar r value that showed only a tendency in F ($r=0.368$; $P=0.059$). In M, percentage bone mass ($r=-0.466$; $P=0.034$; Figure 1C), but not percentage fat or lean mass, was negatively related to $_{REL}LEc$ (i.e. higher percentage bone mass lower $_{REL}LEc$). F showed no relationships of $_{REL}LEc$ and normalised body composition.

Mean of the normalised perimeter z-scores was associated with $RELLEc$ in both cohorts (M $r=0.391$, $P=0.043$; F, $r=0.519$, $P=0.014$). Of the eight individual normalised segment perimeters, six showed significant positive relationships with $RELLEc$ in F ($r=0.415-0.592$; $P=0.002-0.030$) the highest being normalised forearm perimeter (Figure 1D), and two were positively correlated in M ($r=0.430-0.440$; $P=0.029-0.033$). In contrast, normalised segment lengths, masses and MoIs were not related to $RELLEc$ in either cohort.

In the M cohort, MLR analysis performed on all normalised predictor variables significantly correlated with $RELLEc$ revealed that two variables: percentage bone mass (X_2 , 19.9% of the variance explained); and normalised hip perimeter (X_3 , 11.7% additional variance) combined to explain 31.6% of the variance (Figure 2B), which can be predicted using equation 3:

$$\text{Males: } RELLEc \text{ (kcal.kg}^{-1}\text{.km}^{-1}\text{)} = (-9.081 * X_2) + (1.869 * X_3) + 0.231 \quad (3)$$

In the F cohort MLR analysis found only one variable (normalised forearm perimeter, X_4), explained 33.3% of the variance in $RELLEc$ (Figure 2B), and can be predicted using equation 4:

$$\text{Females: } RELLEc \text{ (kcal.kg}^{-1}\text{.km}^{-1}\text{)} = (6.796 * X_4) - 0.112 \quad (4)$$

DISCUSSION

The current study investigated the relationship between putative anthropometric and body composition predictors with running economy in heterogeneous cohorts of male and female runners. Firstly, as expected, greater absolute body size showed moderate to strong associations with absolute running economy ($_{\text{ABSLec}}$ in kcal.km^{-1} ; 21 variables in both M and F cohorts), such that one variable (mean perimeter z-score) explained 68.9% (F) and 49.4% (M) of the variability in absolute energy cost of running. Second, the more common expression of relative running economy had weak to moderate correlations with a smaller number of normalised anthropometric and body composition factors ($_{\text{RELEc}}$ in $\text{kcal.kg}^{-1}.\text{km}^{-1}$; M five variables, F seven variables) predominantly normalised segment perimeters. Combined anthropometric factors explained 31.6% (M, percentage bone mass and normalised hip perimeter) and 33.3% (F, normalised forearm perimeter) of the variance in relative energy cost. Anthropometric measures indicative of a slim physique appear to be important for economical running even when accounting for body mass (i.e. $_{\text{RELEc}}$). This study provides the first comprehensive and robust report of the substantial influence of anthropometric and body composition factors on running economy.

Both male and female cohorts in the current study exhibited a range of $_{\text{ABSLec}}$ (>2-fold range; CVb ~17%) and $_{\text{RELEc}}$ (>1.65-fold range; CVb ~12%) values that were similar to our previous investigations (5, 12) using heterogeneous samples of sub-elite and recreational runners, but greater than for elite runners ($_{\text{RELEc}}$ CVb <8%; 27), likely because running standard is known to influence, and therefore increase the between participant variability in, RE (12). The range of Season's Best Times also confirmed the heterogeneity of the current cohort (M 110-202%; F 110-187% 10 km Road World Record). Between participant variability of the anthropometric and body composition factors was itself quite variable, which might be expected to influence the strength of the relationship of these variables with running economy.

312

313 *Absolute locomotory energy cost*

314 In this investigation, 21 of 27 anthropometric and body composition variables had moderate to
315 strong correlations with absolute L_{Ec} in both the male and female cohorts. Specifically, body
316 mass, BMI, segment perimeters and masses, and calf and thigh MoI were consistently
317 correlated with _{ABS}L_{Ec} in both cohorts, the only consistent exceptions being height and
318 segment lengths. This data indicates the pronounced influence of body mass and girth related
319 variables, but not height and length measurements, on absolute energy cost of running. The
320 relationship between absolute running economy and body mass reported in the present
321 investigation (M $r=0.661$; F $r=0.754$) is in agreement with previous reports (elite runners M
322 $r=0.76$, F $r=0.71$ [1]; obese and healthy boys & men $r=0.98$, [2]). However, the current study
323 is the first evidence that body perimeters may be an even stronger anthropometric predictor of
324 running energy cost than body mass, as the overall index of body perimeters provided the
325 strongest correlates of _{ABS}L_{Ec} in the current analysis (mean of perimeter z-scores: M $r=0.711$
326 and F $r=0.835$). None of the specific perimeter measurements had quite such high correlations
327 with _{ABS}L_{Ec} as the overall index, perhaps due to the greater reliability of the overall value or
328 the fact that larger perimeters of all body segments contribute to increasing whole body _{ABS}L_{Ec}.
329 It may be surprising that some segment perimeters, including mean of perimeter z-scores, were
330 more strongly related to _{ABS}L_{Ec} than MoIs, which might theoretically be expected to be the
331 key anthropometric determinant of RE due to the energy expended in repetitively accelerating
332 the leg backwards and forwards. This may be due to the difficulty in accurately assessing MOI
333 of limb segments that have a complex 3-D, and non-rigid, shape from surface anthropometry.
334 A potentially more sophisticated technique is to use DXA to assess not just segment mass, but
335 also mass distribution, and thus calculate MoI. However this requires access to DXA source
336 data that is not freely available at present. Finally, we assessed MoI about the segment centre

of mass, whereas it could be argued that MoI about the proximal joint centre may be more relevant, although the two would be expected to be closely related. An alternative explanation is that energy dissipation by soft tissue motion during the impact phase of stance has been estimated to account for ~8% and 29% of the net metabolic expenditure of running at 3 m.s⁻¹ and 5 m.s⁻¹ respectively (28), therefore it may be that perimeter and soft tissue mass measures relate more strongly to this cost, rather than the cost of swinging the limb.

The interesting contrast between the relationship of $_{\text{ABSLEc}}$ with segment perimeters (18 out of 18 significant correlations across both cohorts) and MoI (5 out of 6 significant correlations) but not segment lengths (no significant correlations) may be revealing. This is despite the fact that longer segments necessarily contribute to increased MoI. It is possible that longer segments provide a biomechanical advantage that offsets their negative influence of a greater MoI. For example, shorter lower limbs may necessitate higher stride frequencies which are metabolically costly (29) and therefore may negate any benefits of the reduced MoI. Alternatively the relatively modest variability in height and segment lengths in the current cohorts ($\text{CVb} \leq 6.6\%$) may have restricted the scope for relationships with $_{\text{ABSLEc}}$ compared to other more heterogeneous variables.

Subsequently, multiple linear regression analysis showed that mean of perimeter z-scores explained 49.4% (F) and 68.9% (M) of the variance in $_{\text{ABSLEc}}$ (kcal·km⁻¹). Thus an easily measurable anthropometric variable, an overall index of 8 segment perimeters, explained a high proportion of the energy cost of running, and may therefore be of practical importance for estimating human energy expenditure during running.

Relative locomotory energy cost

Running economy is typically expressed relative to body mass which facilitates body mass independent inter-individual comparisons, and we have previously found that in runners ratio scaling (e.g. $\text{kcal.kg}^{-1}.\text{km}^{-1}$) effectively removes the influence of body mass (1, 12), and this was also the case in the current investigation. Thus, the primary aim of the current experiment was to examine the anthropometric and body composition predictors of the relative energy cost of running. Of the 27 anthropometric and body composition variables assessed, we found that five (M) and seven (F) variables were significantly correlated with RELLEc (Table 4). Notably, despite RELLEc being expressed per kg body mass, BMI was positively correlated with RELLEc in M ($r=0.376$, $P=0.037$) with a similar r value and tendency in F ($r=0.368$, $P=0.059$), indicating that runners who are proportionally slimmer relative to their height (less mass per unit height) are more economical. Broadly consistent with these findings for BMI, mean of normalised perimeter z-scores (M $r=0.391$; F $r=0.519$) as well as two (M) and six (F) specific normalised segment perimeters were also positively correlated with relative energy cost (i.e., more slender segments were associated with a lower energy cost). In contrast neither normalised segment masses, lengths and more surprisingly MoIs, were related to RELLEc in either cohort.

Multiple linear regression analysis found that in F normalised forearm perimeter explained 33.3% of the variance in RELLEc , whereas in M two variables (percentage bone mass and normalised hip perimeter) combined to explain 31.6% of the variance in RELLEc (Figure 2B). Percentage bone mass has a reciprocal relationship with soft tissue (i.e., lean and fat, non-bone) mass and, therefore a higher proportion of bone mass is a direct indicator of a lower proportion of soft tissue mass. Accordingly, through its reciprocal relationship with soft tissue mass, the inverse relationship observed between percentage bone mass and RELLEc in M is also an indicator of a relatively slim physique. In F, the specific importance of normalised forearm perimeter for RELLEc is less clear, but could be an overall index of the proportional tissue mass

that is of low utility for running. Overall, the variables contributing to the explained variance in $RELLEc$ all appear to broadly indicate that relative slenderness (normalised segment perimeters in M and F, plus percentage bone/soft tissue mass in M) is beneficial for better/lower running economy.

Overall findings and practical applications

The consistency of our findings across both male and female cohorts of the current study, especially the similar pattern of significant correlations for absolute measures and $ABSLLEc$, but also the underlying importance of slimness for $RELLEc$, and finally the consistent presence of segment perimeters in all four regression equations, provides some confidence in these results. However, given the known anthropometric and body composition differences between males and females (1, 21) it would be surprising if the predictors of running economy were identical in both cohorts. Moreover, why percentage bone mass was an important predictors of $RELLEc$ in M, or why segment perimeters appeared more important in F is currently unclear.

This is the first substantive experimental evidence to support the theory and previous anecdotal evidence suggesting superior running economy and performance are associated with slimmer limbs and a more slender body type (13-19). Based on the findings of the current study the slimmer physique of elite runners (13,14,17) may well explain, at least in part, their better running economy (12). The current study was not able to quantify the extent of cause and effect in any of the relationships examined. However, the intuitive influence and logical rationale for anthropometry influencing economy (7), and due to the magnitude and general consistency of the observed relationships, it seems likely that there is a causal component to these relationships. Future studies could utilise larger populations and/or interventions, as well as more sophisticated statistical techniques, to further explore the nature of the relationships described

by the current experiment. In comparison to the 32-33% of the variance in relative running economy explained by anthropometric and body composition factors in the current experiment, a recent study by our group also reported that ~39% of the variance in running economy could be explained by kinematics (5). It seems possible that the anthropometric and kinematic determinants of running economy may be inter-related and explain somewhat overlapping variance in the determination of running economy, and future work should explore these inter-relationships.

These findings demonstrate that it is relative slenderness, rather than relative segment mass or length that are important considerations for economical running. Assessment of these variables for talent identification and athlete monitoring may be useful for optimising running economy and ultimately performance, as decreasing running economy (higher energy cost) has been shown to predictably impair running performance (3). Although the quantitative relationship and influence of slenderness on the performance of relatively homogenous athletes, compared to running economy in our relatively heterogeneous cohort, remains to be determined. Nonetheless, on a practical basis, within an individual specific envelope these slenderness variables appear to be modifiable. For example, in terms of modifying body composition to achieve a more slender physique and thus improvements in running economy and performance, the optimal scenario would seem to be keeping fat mass to the minimum required for athlete health and having the minimum amount of muscle mass necessary to maintain a requisite running velocity without stressing muscles to the point at which they incur an oxygen debt. On the other hand the heritability of BMI, as a crude indication of slenderness, is ~73% (30), suggesting that the ideal body type for distance running may not be achievable by environmental interventions. From an elite performance perspective this perhaps places more emphasis on talent identification in order to find individuals with the optimal physique for economical running and ultimately performance. These findings therefore provide important

information which may assist a coach or applied practitioner in selecting and preparing athletes for distance running performance.

Conclusion

The results of the current study provide novel and robust evidence to demonstrate that anthropometry and body composition are important predictors of running economy. Indices of relative slenderness, especially segment perimeters, were commonly associated with running economy, indicating that an individual with more slender attributes might be expected to expend less energy and, thus be more economical at any given speed. Given the extent to which measures of anthropometry and body composition can explain variance in relative running economy and, the importance of running economy to distance running events, we encourage coaches, applied practitioners and athletes to incorporate anthropometric and body composition assessments into their testing routine as an aid to identifying talented athletes and preparing athletes for optimal performance.

Acknowledgements

This work was financially supported by MAS Holdings, Sri Lanka.

Conflict of interest

455 None of the authors have any conflict of interest to disclose. The results of the present study
456 do not constitute endorsement by ACSM. We declare that the results of the present study are
457 presented clearly, honestly, and without fabrication, falsification, or inappropriate data
458 manipulation.

REFERENCES

1. Shaw AJ, Ingham SA, Folland JP. The valid measurement of running economy in runners. *Med Sci Sports Exerc.* 2014; 46(10): 1968-1973.
2. Taboga P, Lazzer S, Fesshatsion R, Agosti F, Sartorio A, di Prampero PE. Energetics and mechanics of running men: the influence of body mass. *Eur J Appl Physiol.* 2012; 112(12): 4027-4033.
3. Hoogkamer W, Kipp S, Spiering, BA, Kram R. Altered running economy directly translates to altered distance-running performance. *Med Sci Sports Exerc.* 2016; 48(11): 2175-2180.
4. McLaughlin JE, Howley ET, Bassett DR, Thompson DL, Fitzhugh EC. Test of the classical model for predicting endurance running performance. *Med Sci Sports Exerc.* 2010; 42: 991-997.
5. Folland JP, Allen SJ, Black MI, Handsaker JC, Forrester SE. Running technique is an important component of running economy and performance. *Med Sci Sports Exerc.* 2017; 49(7): 00-00.

6. Morgan DW, Bransford DR, Costill DL, Daniels JT, Howley ET, Krahenbuhl GS. Variation in the aerobic demand of running among trained and untrained subjects. *Med Sci Sports Exerc.* 1995; 27(3): 404-409.
7. Anderson T. Biomechanics and running economy. *Sports Med.* 1996; 22(2): 76-89.
8. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med.* 2004; 34(7): 465-485.
9. Lacour JR, Bourdin M. Factors affecting the energy cost of level running at a submaximal speed. *Eur J Appl Physiol.* 2015; 115(4): 651-673.
10. Fletcher JR, Esau SP, MacIntosh BR. Economy of running: beyond the measurement of oxygen uptake. *J Appl Physiol.* 2009; 107(6): 1918-1922.
11. Myers MJ, Steudel K. Effect of limb mass and its distribution on the energetic cost of running. *J Exp Biol.* 1985; 116: 363-373.
12. Black MI, Handsaker JC, Allen SJ, Forrester SE, Folland JP. Is there an optimum speed for economical running? *Int J Sports Physiol Perform.* 2017; 13(1): 75-81.
13. Kong PW, de Heer H. Anthropometric, gait and strength characteristics of Kenyan distance runners. *J Sports Sci Med.* 2008; 7: 499-504.
14. Lucia A, Esteve-Lanao J, Olivan J et al. Physiological characteristics of the best Eritrean runners-exceptional running economy. *Appl Physiol Nutr Metab.* 2006; 31(5): 530-540.
15. Lucia A, Olivan J, Bravo J, Gonzalez-Freire M, Foster C. The key to top-level endurance running performance: a unique example. *Br J Sports Med.* 2008; 42(3): 172-174.
16. Santos-Concejero J, Olivan J, Mate-Munoz JL et al. Gait-cycle characteristics and running economy in Elite Eritrean and European runners. *Int J Sports Physiol Perform.* 2015; 10(3): 381-387.

17. Vernillo G, Schena F, Beraredlli C et al. Anthropometric characteristics of top-class Kenyan marathon runners. *J Sports Med Phys Fitness*. 2013; 53: 403-408.
18. Larsen HB. Kenyan dominance in distance running. *Comp Biochem Physiol A Mol Integr Physiol*. 2003; 136(1): 161-170.
19. Foster C, Lucia A. Running economy: the forgotten factor in elite performance. *Sports Medicine*, 2007; 37: 316-319.
20. Mooses M, Mooses K, Haile DW, Durussel J, Kaasik P, Pitsalidis YP. Dissociation between running economy and running performance in elite Kenyan distance runners. *J Sports Sci*. 2015; 33(2): 136-144.
21. Pate RR, Macera CA, Bailey SP, Bartoli WP, Powell KE. Physiological, anthropometric, and training correlates of running economy. *Med Sci Sports Exerc*. 1992; 24(10): 1128-1133.
22. International Association of Athletics Federations. (2014). Website [Internet]. IAAF Scoring tables of athletics-outdoors. Accessed 2015 January 5: <http://www.iaaf.org/about-iaaf/documents/technical>
23. Yeadon MR. The simulation of aerial movement: II. A mathematical inertia model of the human body. *J Biomech*. 1990; 23(1): 67-74.
24. Peronnet F, Massicote D. Table of nonprotein respiratory quotient: an update. *Can J Sport Sci*. 1991; 16(1): 23-29.
25. Jeukendrup AE, Wallis GA. Measurement of substrate oxidation during exercise by means of gas exchange measurements. *Int J Sports Med*. 2005; 26(1 Suppl): S28-S37.
26. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc Series B Stat Methodol*. 1995; 57: 289-300.

27. Shaw AJ, Ingham SA, Atkinson G, Folland JP. The correlation between running economy and maximal oxygen uptake: cross-sectional and longitudinal relationships in highly trained runners. *Plos One*. 2015; 10(4): e0123101.
28. Riddick, RC, Kuo, AD. Soft tissues store and return mechanical energy in human running, *J Biomech*. 2016; 49(3): 436-441.
29. Doke J, Donelan JM, Kuo AD. Mechanics and energetics of swinging the human leg. *J. Exp. Biol*. 2005; 208: 439-445.
30. Min J, Chiu DT, Wang Y. Variation in the heritability of body mass index based on diverse twin studies: a systematic review. *Obes Rev*. 2013; 14(11): 871-882.

Figure captions

Figure 1 Scatterplots of the relationship between: absolute locomotory energy cost and mean perimeter z-score in males (A, $n=45$, $r=0.711$, $P<0.001$) and females (B, $n=40$, $r=0.835$, $P<0.001$); relative locomotory energy cost and percentage bone mass in males (C, $n=45$, $r=-0.466$, $P=0.034$) or normalised forearm perimeter in females (D, $n=40$, $r=0.592$, $P=0.014$).

Figure 2 Anthropometric and body composition determinants of absolute (A, $\text{kcal}\cdot\text{km}^{-1}$) and relative (B, $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) locomotory energy cost in male ($n=45$; black) and female ($n=40$; white) cohorts from stepwise multiple linear regression analyses.

Table 1 Descriptive performance and physiology data of the participants. Performance was assessed as season's best time over distances from 1,500 m to the marathon, converted to an equivalent 10 km road time using IAAF points scores and expressed as a percentage (%) of the 10 km road World Record. *sLTP*, speed of lactate turnpoint during the laboratory incremental treadmill test. Absolute (*ABSLEc*) and relative (*RELLEc*) locomotory energy cost was the average of measurements at 10, 11 and 12 km.h⁻¹. Data presented as mean ± SD (range).

	Males (n=45)	Females (n=40)
% 10 km Road World Record	142 ± 24 (110 – 202)	148 ± 22 (110 – 187)
<i>sLTP</i> (km h ⁻¹)	17.0 ± 2.0 (13.0 – 21.0)	14.0 ± 2.0 (12.0 – 19.0)
$\dot{V}O_2\text{max}$ (ml·kg ⁻¹ ·min ⁻¹)	62.8 ± 7.2 (48.0 – 79.8)	54.3 ± 6.4 (42.2 – 71.9)
<i>ABSLEc</i> (kcal·km ⁻¹)	54.3 ± 9.1 (31.3 – 76.7)	44.6 ± 7.6 (27.8 – 60.8)
<i>RELLEc</i> (kcal·kg ⁻¹ ·km ⁻¹)	0.79 ± 0.10 (0.54 – 1.07)	0.79 ± 0.09 (0.57 – 0.94)

Table 2 Descriptive data for absolute body size, and absolute and normalised anthropometric and body composition data of the participants. For the normalised variables section titles indicate the denominator variable used for normalisation. Data are mean $\pm$ SD.

Predictor variable	Males (n=45)		Females (n=40)	
	Absolute	Normalised	Absolute	Normalised
Body Size				
Height, H (m)	1.79 $\pm$ 0.06	-	1.65 $\pm$ 0.07	-
Body mass, BM (kg)	68.6 $\pm$ 6.1	-	56.0 $\pm$ 6.6	-
BMI (kg.m ⁻²)	21.5 $\pm$ 1.4	-	20.4 $\pm$ 1.8	-
Body Composition				
	(kg)	/BM (%BM)	(kg)	/BM (%BM)
Fat mass	9.6 $\pm$ 3.0	13.9 $\pm$ 3.9	12.5 $\pm$ 3.1	22.1 $\pm$ 4.4
Lean mass	55.9 $\pm$ 5.2	81.6 $\pm$ 3.8	41.1 $\pm$ 4.9	73.6 $\pm$ 4.3
Bone mass	3.05 $\pm$ 0.37	4.46 $\pm$ 0.44	2.38 $\pm$ 0.32	4.25 $\pm$ 0.33
Segment perimeter				
	(cm)	/H (-)	(cm)	/H (-)
Calf	35.7 $\pm$ 1.8	0.20 $\pm$ 0.01	34.2 $\pm$ 2.1	0.21 $\pm$ 0.01
Thigh	50.7 $\pm$ 2.4	0.28 $\pm$ 0.01	48.0 $\pm$ 3.5	0.29 $\pm$ 0.02
Hip	92.2 $\pm$ 3.4	0.52 $\pm$ 0.02	90.0 $\pm$ 4.7	0.54 $\pm$ 0.03
Waist	76.8 $\pm$ 4.0	0.43 $\pm$ 0.02	69.0 $\pm$ 4.5	0.42 $\pm$ 0.03
Chest	89.3 $\pm$ 3.5	0.50 $\pm$ 0.02	81.1 $\pm$ 3.6	0.49 $\pm$ 0.02
Neck	34.8 $\pm$ 1.5	0.19 $\pm$ 0.01	30.7 $\pm$ 1.7	0.19 $\pm$ 0.01
Upper-arm	26.1 $\pm$ 1.9	0.15 $\pm$ 0.01	23.4 $\pm$ 2.0	0.14 $\pm$ 0.01
Forearm	24.7 $\pm$ 1.3	0.14 $\pm$ 0.01	22.1 $\pm$ 1.4	0.13 $\pm$ 0.01
Segment length				
	(cm)	/H (-)	(cm)	/H (-)
Foot	27.3 $\pm$ 1.5	0.15 $\pm$ 0.01	24.0 $\pm$ 1.6	0.15 $\pm$ 0.01
Calf	38.6 $\pm$ 2.0	0.22 $\pm$ 0.01	35.3 $\pm$ 2.2	0.21 $\pm$ 6.4 x 10 ⁻³
Thigh	46.2 $\pm$ 2.3	0.26 $\pm$ 0.01	42.1 $\pm$ 2.4	0.25 $\pm$ 0.01
Leg	92.7 $\pm$ 4.0	0.52 $\pm$ 0.01	84.3 $\pm$ 5.1	0.51 $\pm$ 0.02
Segment mass				
	(kg)	/BM (-)	(kg)	/BM (-)
Foot	1.01 $\pm$ 0.11	1.5 x 10 ⁻² $\pm$ 1.2 x 10 ⁻³	0.75 $\pm$ 0.09	1.4 x 10 ⁻² $\pm$ 1.35 x 10 ⁻³
Calf	3.02 $\pm$ 0.34	4.4 x 10 ⁻² $\pm$ 3.1 x 10 ⁻³	2.58 $\pm$ 0.38	4.6 x 10 ⁻² $\pm$ 3.3 x 10 ⁻³
Thigh	8.30 $\pm$ 0.87	0.12 $\pm$ 5.0 x 10 ⁻³	7.12 $\pm$ 1.04	0.13 $\pm$ 5.3 x 10 ⁻³
Leg	12.3 $\pm$ 1.23	0.18 $\pm$ 6.5 x 10 ⁻³	10.5 $\pm$ 1.44	0.19 $\pm$ 6.4 x 10 ⁻³
Arm	3.48 $\pm$ 0.40	1.5 x 10 ⁻³ $\pm$ 1.9 x 10 ⁻⁴	2.57 $\pm$ 0.39	1.7 x 10 ⁻³ $\pm$ 2.6 x 10 ⁻⁴
Moment of inertia				
	(kg $\cdot$ m ²)	(/BM/H ²) (-)	(kg $\cdot$ m ²)	(/BM/H ²) (-)
Foot	3.7 x 10 ⁻³ $\pm$ 9.0 x 10 ⁻⁴	1.7 x 10 ⁻⁵ $\pm$ 2.9 x 10 ⁻⁶	2.3 x 10 ⁻³ $\pm$ 7.4 x 10 ⁻⁴	1.5 x 10 ⁻⁵ $\pm$ 3.2 x 10 ⁻⁶
Calf	6.3 x 10 ⁻² $\pm$ 1.2 x 10 ⁻²	2.9 x 10 ⁻⁴ $\pm$ 3.0 x 10 ⁻⁵	4.4 x 10 ⁻² $\pm$ 9.5 x 10 ⁻³	2.9 x 10 ⁻⁴ $\pm$ 2.5 x 10 ⁻⁵
Thigh	1.57 x 10 ⁻¹ $\pm$ 2.8 x 10 ⁻²	7.1 x 10 ⁻⁴ $\pm$ 6.3 x 10 ⁻⁵	1.1 x 10 ⁻¹ $\pm$ 2.5 x 10 ⁻²	7.3 x 10 ⁻⁴ $\pm$ 5.1 x 10 ⁻⁵

Table 3 Pearson's product moment correlation coefficients between absolute locomotory energy cost ($\text{kcal}\cdot\text{km}^{-1}$) and absolute anthropometric and body composition variables for males ($n=45$) and females ($n=40$).

Predictor variable	Males	Females
Body Size		
Height (m)	0.265	0.286
Body mass (kg)	0.661***	0.754***
BMI ($\text{kg}\cdot\text{m}^{-2}$)	0.610***	0.716***
Body composition (kg)		
Fat mass	0.478**	0.503***
Lean mass	0.488***	0.655***
Bone mass	0.143	0.549***
Segment perimeter (cm)		
Calf	0.586***	0.734***
Thigh	0.479**	0.735***
Hip	0.699***	0.618***
Waist	0.504***	0.534***
Chest	0.474**	0.563***
Neck	0.600***	0.694***
Upper-arm	0.533***	0.746***
Forearm	0.432**	0.805***
Mean Perimeter (z-score)	0.711***	0.835***
Segment length (cm)		
Foot	0.147	0.209
Calf	0.191	0.266
Thigh	0.023	0.278
Leg	0.079	0.265
Segment mass (kg)		
Foot	0.331*	0.357*
Calf	0.546***	0.701***
Thigh	0.644***	0.747***
Leg	0.635***	0.747***
Arm	0.442**	0.784***
Moment of inertia ($\text{kg}\cdot\text{m}^2$)		
Foot	0.332*	0.203
Calf	0.556***	0.514***
Thigh	0.585***	0.574***

P values were corrected for multiple tests and significance is shown by *** $P\leq 0.001$; ** $P\leq 0.01$; * $P\leq 0.05$

Table 4 Pearson's product moment correlation coefficients between relative locomotory energy cost ($\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) and absolute body size, normalised anthropometric and body composition variables for males ($n=45$) and females ($n=40$). For the normalised variables section titles indicate the denominator variable used for normalisation (in brackets).

Predictor variable	Males	Females
Absolute Body Size		
Height, H (m)	-0.116	-0.260
Body mass, BM (kg)	0.184	0.092
BMI ($\text{kg}\cdot\text{m}^{-2}$)	0.376*	0.368 [#]
Normalised Body Composition (/BM)		
Fat mass (%)	0.290	0.081
Lean mass (%)	-0.249	-0.071
Bone mass (%)	-0.466*	-0.169
Normalised segment perimeter (/H)		
Calf (-)	0.430*	0.469*
Thigh (-)	0.233	0.461*
Hip (-)	0.440*	0.275
Waist (-)	0.264	0.415*
Chest (-)	0.240	0.277
Neck (-)	0.392 [#]	0.491*
Upper-arm (-)	0.311	0.472*
Forearm (-)	0.166	0.592**
Mean Perimeter (z-score)	0.391*	0.519**
Normalised segment length (/H)		
Foot (-)	0.077	0.047
Calf (-)	-0.019	-0.035
Thigh (-)	-0.224	-0.162
Leg (-)	-0.228	-0.114
Normalised segment mass (/BM)		
Foot (-)	-0.303	-0.289
Calf (-)	0.066	0.143
Thigh (-)	0.160	0.159
Leg (-)	0.099	0.144
Arm (-)	-0.295	-0.209
Normalised moments of inertia (/BM/H²)		
Foot (-)	-0.057	-0.381 [#]
Calf (-)	0.315	-0.148
Thigh (-)	0.313	-0.192

P values were corrected for multiple tests and significance is shown by *** $P\leq 0.001$; ** $P\leq 0.01$;

* $P\leq 0.05$; [#] $P\leq 0.07$

Predictor variable	Males (n=45)		Females (n=40)	
	Absolute	Normalised	Absolute	Normalised
Body Size				
Height, H (m)	1.79 ± 0.06	-	1.65 ± 0.07	-
Body mass, BM (kg)	68.6 ± 6.1	-	56.0 ± 6.6	-
BMI (kg.m ⁻²)	21.5 ± 1.4	-	20.4 ± 1.8	-
Body Composition				
	(kg)	/BM (%BM)	(kg)	/BM (%BM)
Fat mass	9.6 ± 3.0	13.9 ± 3.9	12.5 ± 3.1	22.1 ± 4.4
Lean mass	55.9 ± 5.2	81.6 ± 3.8	41.1 ± 4.9	73.6 ± 4.3
Bone mass	3.05 ± 0.37	4.46 ± 0.44	2.38 ± 0.32	4.25 ± 0.33
Segment perimeter				
	(cm)	/H (-)	(cm)	/H (-)
Calf	35.7 ± 1.8	0.20 ± 0.01	34.2 ± 2.1	0.21 ± 0.01
Thigh	50.7 ± 2.4	0.28 ± 0.01	48.0 ± 3.5	0.29 ± 0.02
Hip	92.2 ± 3.4	0.52 ± 0.02	90.0 ± 4.7	0.54 ± 0.03
Waist	76.8 ± 4.0	0.43 ± 0.02	69.0 ± 4.5	0.42 ± 0.03
Chest	89.3 ± 3.5	0.50 ± 0.02	81.1 ± 3.6	0.49 ± 0.02
Neck	34.8 ± 1.5	0.19 ± 0.01	30.7 ± 1.7	0.19 ± 0.01
Upper-arm	26.1 ± 1.9	0.15 ± 0.01	23.4 ± 2.0	0.14 ± 0.01
Forearm	24.7 ± 1.3	0.14 ± 0.01	22.1 ± 1.4	0.13 ± 0.01
Segment length				
	(cm)	/H (-)	(cm)	/H (-)
Foot	27.3 ± 1.5	0.15 ± 0.01	24.0 ± 1.6	0.15 ± 0.01
Calf	38.6 ± 2.0	0.22 ± 0.01	35.3 ± 2.2	0.21 ± 6.4 x 10 ⁻³
Thigh	46.2 ± 2.3	0.26 ± 0.01	42.1 ± 2.4	0.25 ± 0.01
Leg	92.7 ± 4.0	0.52 ± 0.01	84.3 ± 5.1	0.51 ± 0.02
Segment mass				
	(kg)	/BM (-)	(kg)	/BM (-)
Foot	1.01 ± 0.11	1.5 x 10 ⁻² ± 1.2 x 10 ⁻³	0.75 ± 0.09	1.4 x 10 ⁻² ± 1.35 x 10 ⁻³
Calf	3.02 ± 0.34	4.4 x 10 ⁻² ± 3.1 x 10 ⁻³	2.58 ± 0.38	4.6 x 10 ⁻² ± 3.3 x 10 ⁻³
Thigh	8.30 ± 0.87	0.12 ± 5.0 x 10 ⁻³	7.12 ± 1.04	0.13 ± 5.3 x 10 ⁻³
Leg	12.3 ± 1.23	0.18 ± 6.5 x 10 ⁻³	10.5 ± 1.44	0.19 ± 6.4 x 10 ⁻³
Arm	3.48 ± 0.40	1.5 x 10 ⁻³ ± 1.9 x 10 ⁻⁴	2.57 ± 0.39	1.7 x 10 ⁻³ ± 2.6 x 10 ⁻⁴
Moment of inertia				
	(kg · m ²)	(/BM/H ²) (-)	(kg · m ²)	(/BM/H ²) (-)
Foot	3.7 x 10 ⁻³ ± 9.0 x 10 ⁻⁴	1.7 x 10 ⁻⁵ ± 2.9 x 10 ⁻⁶	2.3 x 10 ⁻³ ± 7.4 x 10 ⁻⁴	1.5 x 10 ⁻⁵ ± 3.2 x 10 ⁻⁶
Calf	6.3 x 10 ⁻² ± 1.2 x 10 ⁻²	2.9 x 10 ⁻⁴ ± 3.0 x 10 ⁻⁵	4.4 x 10 ⁻² ± 9.5 x 10 ⁻³	2.9 x 10 ⁻⁴ ± 2.5 x 10 ⁻⁵
Thigh	1.57 x 10 ⁻¹ ± 2.8 x 10 ⁻²	7.1 x 10 ⁻⁴ ± 6.3 x 10 ⁻⁵	1.1 x 10 ⁻¹ ± 2.5 x 10 ⁻²	7.3 x 10 ⁻⁴ ± 5.1 x 10 ⁻⁵