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# Anthropometric and physiological determinants of running economy and performance from Estonian recreational to Kenyan national level distance runners

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PRESS

Institute of Sport Pedagogy and Coaching Sciences, Faculty of Exercise and Sport Sciences, Centre of Behavioural, Social, and Health Sciences, University of Tartu, Tartu, Estonia

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In Papers I, II and III Martin Mooses had primary responsibility for protocol development, enrolment of the participants, performing measurements, data analysis, and writing the manuscripts.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| BMI | body mass index |
| CR | competitive level runners |
| DXA | dual energy X-ray absorptiometry |
| E/T ratio | extremity (*triceps, front thigh, medial calf*)/trunk (*subscapular, iliac crest, abdominal*) skinfold ratio |
| frac | relative duration of the last uncompleted velocity |
| HR | heart rate |
| IAAF | International Association of Athletics Federations |
| LD | long-distance runners |
| MD | middle-distance runners |
| RE | running economy |
| RR | recreational level runners |
| t | time |
| $t_{max}$ | maximal running time on treadmill |
| v | speed |
| $v\dot{V}O_{2max}$ | speed at maximal oxygen uptake intensity |
| VE | minute ventilation |
| vlast | last completed velocity |
| VT1 | first ventilatory threshold |
| VT1track | first ventilatory threshold on running track |
| VT1tread | first ventilatory threshold on treadmill |
| VT2 | second ventilatory threshold |
| VT2time | second ventilatory threshold time |
| VT2track | second ventilatory threshold on running track |
| VT2tread | second ventilatory threshold on treadmill |
| vVT1 | speed at first ventilatory threshold |
| vVT1tread | speed at first ventilatory threshold on treadmill |
| vVT2 | speed at second ventilatory threshold |
| vVT2tread | speed at second ventilatory threshold on treadmill |
| $\dot{V}O_2 16$ | oxygen uptake at the speed of 16 $km \cdot h^{-1}$ |
| $\dot{V}O_{2max}$ | maximal oxygen uptake |

# 1. INTRODUCTION

East African runners have dominated distance running for more than 40 years. Distance runners from Kenya hold over 55% of positions in all-time world top 20 list (IAAF, 2012). The majority of Ethiopian (Scott, et al., 2003) and Kenyan runners originate from the same geographical location, namely the Great Rift Valley region, and typically belong to the same ethnic groups, named Oromo and Kalenjin, respectively (Onywera, et al., 2006). Proposed explanations for the unprecedented success of Kenyan runners have included genetic, environmental, cultural, socioeconomic, lifestyle and training factors (Hamilton, 2000; Larsen, 2003; Myburgh, 2003; Pitsiladis, et al., 2004). From the early study conducted by Saltin et al. (1995) until to date (Prommer, et al., 2010) there is lack of evidence for higher maximal oxygen uptake ($\dot{V}O_{2max}$) values in East African runners compared with Caucasian counterparts. Thus, it appears that elite East African runners do not have any specific advantage over non-African runners in terms of $\dot{V}O_{2max}$ despite clear difference in performance (Wilber & Pitsiladis, 2012). Therefore successful performance of distance runners, specifically those from East Africa, is generally attributed to better running economy (RE) (Foster & Lucia, 2007; Larsen, 2003; Saltin, et al., 1995; Weston, et al., 2000). On the contrary, more recently it has been demonstrated that RE of North African runners is not related to their performance, furthermore, high level Spanish runners were more economical than their North African counterparts (Santos-Concejero, et al., 2013). Altogether, to date there is no consensus which factors are responsible for superior RE. In addition, there is equivocal data about how RE is related to running performance, and about RE between homogenous group of middle- and long-distance runners.

Scientific community has agreed that RE is not determined only by one parameter but it is rather more complex factor to look at especially at highest level of human performance (Foster & Lucia, 2007; Saunders, et al., 2004) and therefore for better understanding of the interaction between RE, performance, body composition and anthropometrics on different level of distance running is needed. Thus, the aim of the current thesis was to investigate RE and performance in relation with physiological and anthropometric parameters in recreational and national level Estonian runners as well as national level Kenyan distance runners.

# 2. LITERATURE REVIEW

## 2.1. Running economy and maximal oxygen uptake as determinants of running performance

Running performance is related to a variety of physiological characteristics in national (Maldonado, et al., 2002) and elite (Rabadan, et al., 2011) level middle- and long-distance runners. The physiological determinants of distance running performance include $\dot{V}O_{2max}$, lactate threshold, and RE (Fletcher, et al., 2009; Joyner & Coyle, 2008; Midgley, et al., 2007). These three determinants explain over 70% of the between subject variance in distance running performance (Pate & Branch, 1992). Previous studies have reported high but similar $\dot{V}O_{2max}$ values in Kenyan and Caucasian distance runners (Prommer, et al., 2010; Saltin, et al., 1995) and therefore recent research attention has shifted to other possible determinants of the superior performances of Kenyan runners, including RE, that is believed to be largely affected by anthropometric parameters (Billat, et al., 2001; Larsen, 2003; Tam, et al., 2012) or intrinsic morphological and physiological properties (Raichlen, et al., 2011; Scholz, et al., 2008). RE is defined as the amount of metabolic energy needed to displace a unit of body mass over a certain distance or, equivalently, the metabolic power per unit of body mass required to run at a certain speed (Scholz, et al., 2008). More economical runners use less oxygen than less economical runners at the same steady state speed or at the same relative intensity. Even at the highest levels of human performance RE can vary from 20−30% (Raichlen, et al., 2011; Scholz, et al., 2008) up to 30−40% (Joyner & Coyle, 2008). To date there is no clear consensus how RE is related to running performance. It has been demonstrated that better RE refers to higher performance (Fletcher, et al., 2009). However, some studies suggest no relationship (Foster, et al., 1977; Santos-Concejero, et al., 2013; Williams & Cavanagh, 1987).

Therefore questions how to measure RE has been raised more recently (Fletcher, et al., 2009). Earlier studies (Lucia, et al., 2006; Weston, et al., 2000) have evaluated RE at one particular speed for all participants. This may be one of the reasons why RE defined by oxygen uptake at a given speed may have as high variability as 30−40% among individuals (Joyner & Coyle, 2008). Accordingly Fletcher et al. (2009) argued that RE should be compared between individuals at a similar relative running intensity rather than at the same running speed. Comparing different athletes at the same absolute running speeds does not acknowledge differences in speed associated with the lactate threshold or differences in substrate utilization associated with differences in intensity relative to $\dot{V}O_{2max}$ (Fletcher, et al., 2009). It has been found that elite runners have better RE than runners at lower performance level (Pollock, 1977). However, it is far less studied whether high level runners have better RE at their individual ventilatory thresholds (VT1 and VT2) compared with runners at lower performance level.

It has been found that national (Maldonado, et al., 2002) and elite (Rabadan, et al., 2011; Svedenhag & Sjödin, 1984) level long-distance runners present significantly higher $\dot{V}O_{2max}$ values than middle-distance runners. In addition, elite long-distance runners (Rabadan, et al., 2011) demonstrate higher speed at second ventilatory threshold (VT2) compared to middle-distance runners (Beaver, et al., 1986). Rabadan et al. (2011) also found that middle- and long-distance runners have different $\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$), maximal speed on treadmill, speed at ventilation threshold 1 (VT1) and 2 (VT2) and, RE at VT1 and VT2. Similar to Rabadan et al. (2011) earlier Maldonado et al. (2002) found that long-distance runners (5 000–10 000 m) had significantly higher $\dot{V}O_{2max}$ than marathon runners or middle-distance runners (800–1 500 m). $\dot{V}O_{2max}$ values in elite male runners increase in running distances up to 3 000 m, showing a greater importance of this parameter for performance prediction, while $\dot{V}O_{2max}$ appears to be similar from 3 000 m to marathon distances thus indicating similar importance of $\dot{V}O_{2max}$ for these running events (Legaz, et al., 2007). Furthermore, middle- and long-distance runners use different training volumes and intensities, which lead to different adaptations in aerobic performance parameters (Rabadan, et al., 2011). Elite level distance runners' competition lasts from 1:41 (min:s) up to more than 2 hours. It is important to distinguish middle- and long-distance events because training to compete about 1:41 (min:s) is markedly different to those to compete about 2 hours. Top level long-distance runners (5 000 and 10 000 m) usually run 160–180 km per week during the preparatory period and aim to maintain the maximum aerobic speed, middle-distance runners (800 and 1 500 m) run 130–140 km and focus their training on increasing their maximum aerobic power (Rabadan, et al., 2011).

To date there is equivocal data about interaction between RE and $\dot{V}O_{2max}$ and how these two parameters are related to running performance in different performance level distance runners.

## 2.2. Anthropometry and body composition as determinants of running performance and economy

Body composition and anthropometric assessment provide the sports physician with useful information on the health state of the athlete to plan specific training loads in the most appropriate way in these events where athlete's body mass is a function of the performance (Giampietro, et al., 2011). In addition to different physiological parameters, several anthropometric and body composition values are known to be associated with running performance in elite middle- and long-distance (Arrese & Ostariz, 2006) and ultramarathon (Knechtle, et al., 2008) runners. For example, body height and mass (Maldonado, et al., 2002), fat and fat-free mass (Winter & Hamley, 1976), arm circumference (Knechtle, et al., 2008), different lower limb skinfolds and circumferences (Legaz & Eston, 2005) and also sum of three (Kong & de Heer, 2008) and six (Legaz & Eston,

2005) skinfolds have been related to distance running performance. In addition Arrese and Ostariz (2006) found high correlation between the front thigh and medial calf skinfolds and 1 500 m run time in high level runners. Similar correlation was found between front thigh and medial calf skinfolds and 10 000 m run time. They concluded that skinfold thickness in the lower limb are positively associated with running time over several distances and may be a useful predictor of athletic performance. Tanaka and Matsuura (1982) noted that the circumference of chest and thigh and the length of the upper leg correlates best with running performances in distances 800 m, 1 500 m and 5 000 m distances, whereas upper arm circumferences has an association with 10 000 m running performances.

Previous studies with middle- and long-distance runners have found that excellent RE is associated at least partly with anthropometric characteristics (Kong & de Heer, 2008; Lucia, et al., 2006; Saltin, et al., 1995). In the study with top-level Caucasian and East African runners Lucia et al. (2006) summarise that top-level Eritrean runners are characterised by a high RE compared with Spanish controls. Their improved RE is most likely associated with anthropometric characteristics, rather than with any specific metabolic property of the working muscle. On the other hand, in case study with men 2007 Cross-Country World Champion Lucia et al. (2008) showed that the anthropometric characteristics of this runner (height, body mass, body mass index, proportional leg length) were more similar to most Spanish runners, who tend to be less linear and proportionately less long-legged individuals than top level Kenyan runners. Nevertheless, his running economy was one of the lowest ever published (150 $O_2$ ml·kg$^{-1}$·km$^{-1}$ on 17, 19 and 21 km·h$^{-1}$) (Lucia, et al., 2008). Body shape and mass of the legs may play an important role. Elite East African distance runners have a low body mass index (BMI) and a more slender body shape compared to Caucasian elite distance runners (Saltin, et al., 1995).

Despite a number of studies describing different anthropometric parameters in top level East African (Kong & de Heer, 2008; Lucia, et al., 2006; Lucia, et al., 2008) and Caucasian runners (Arrese & Ostariz, 2006; Knechtle, et al., 2008; Legaz & Eston, 2005) there is a paucity of studies examining different leg ratios and the relationship with running performance and/or RE. However, there is a study (Lucia, et al., 2008) that has described leg length to body height ratio in top-level Spanish distance runners in comparison with one of the best Eritrean runner. Runners with proportionally smaller amount of body mass concentrated in the extremities, particularly in the legs, would perform less work moving their body segments during running, if all other factors are unchanged (Myers & Steudel, 1985). Therefore, leg mass and the distribution of leg mass might be important characteristics in performance of distance runners (Myers & Steudel, 1985). Overall, previous studies with middle- and long-distance runners have found that excellent RE is associated at least partly with anthropometric characteristics (Kong & de Heer, 2008; Lucia, et al., 2006; Saltin, et al., 1995).

Legaz and Eston (2005) suggested that anthropometric assessment of top class athletes should include an evaluation of all skinfolds. They (Legaz & Eston 2005) concluded that the loss of body fat appears to be specific to the muscular groups used during training. The lower limb skinfolds may be particularly useful predictor of running performance. They provided evidence that changes in running performance are related to changes in (i) the sum of six skinfolds; (ii) the medial calf and anterior thigh skinfold and (iii) extremity (triceps, front thigh, medial calf)/trunk (subscapular, iliac crest, abdominal) skinfold ratio. Indeed, body composition of runners has been examined extensively, however, most of these studies have been conducted with relatively heterogeneous groups of runners (Arrese & Ostariz, 2006). Anthropometry has been a popular tool for the assessment of body fat among high level distance runners but dual energy X-ray absorptiometry (DXA) is technically more sophisticated and accurate method for body composition assessment (Ball, et al., 2004). Despite significant and high correlation between DXA measured percent body fat and predicted percent body fat by the anthropometric equations from Jackson and Pollock (1978), it has been found that Jackson-Pollock equations underestimate percent of body fat approximately 3% compared to DXA (Ball, et al., 2004).

More recently the importance of tendons in relation to RE have emerged (Raichlen, et al., 2011; Scholz, et al., 2008). The amount of energy stored in tendon depends on the mechanical properties of the tendon (compliance and rest length) and the force that stretches the tendon. For a given kinematic pattern, and hence kinetic pattern, tendon force is inversely related to the moment arm of the tendon (Scholz, et al., 2008). The Achilles tendon moment arm is the perpendicular distance from the ankle joint center of rotation to the line of action of the Achilles tendon and the shorter the moment arm, the greater storage and release of elastic strain energy, and therefore reduced energy cost (Raichlen, et al., 2011). Any energy stored in the tendon does not have to be generated by the contractile element. Reducing contractile element energy generation is expected to lead to lower metabolic cost, because energy generation by contractile element is metabolically the most expensive process in muscle contraction (Scholz, et al., 2008). A well replicated finding in this field, albeit in heterogeneous groups of distance runners is the observation that RE is a function of anatomical differences in Achilles tendon moment arm (Raichlen, et al., 2011; Scholz, et al., 2008). Specifically, a smaller Achilles tendon moment arm has been associated with better RE in a small heterogeneous group of distance runners with various body mass and $\dot{V}O_{2max}$ values (Scholz, et al., 2008).

Although body composition has been subject of interest for a long time, there is lack of studies evaluating body composition and different body mass ratios in distance runners using DXA method. Similarly, anthropometric parameters are intensively studied, however to date different anthropometrical ratios have not been studied profoundly in distance runners.

# 3. THE AIM OF THE STUDY

The general purpose of the current thesis was to investigate RE and performance in relation with physiological, anthropometric and body composition parameters in Estonian recreational and national level runners, as well as in national level Kenyan distance runners on track and on treadmill conditions.

Specific aims of the study were:

1. To compare anthropometric, body composition and physiological parameters that are related to running performance in Estonian national level middle- and long-distance runners (Study I).
2. To compare RE between Estonian competitive and recreational level distance runners at their individual VT1 and VT2 on track (Study II).
3. To compare body composition parameters that are related to the individual RE in Estonian competitive and recreational level distance runners (Study II).
4. To examine which anthropometric parameters are related to RE and running performance in homogenous group of national level Kenyan distance runners (Study III).
5. To examine the relationship between RE and running performance in homogenous group of national level Kenyan distance runners (Study III).

# 4. METHODS

## 4.1. Sample sizes and measurements taken in study I, II and III

The current dissertation is combined of three different studies (Table 1). Study I and II were conducted with Estonian middle- and long-distance runners and were designed to evaluate RE on treadmill and in field conditions in relation with anthropometric and body composition parameters. Study III was carried out with national level Kenyan middle- and long-distance runners in Kenya, using same equipment and similar methods as in Estonia, in order to evaluate their running performance and RE in relation with anthropometric parameters.

**Table 1.** Sample size and measurements from study I, II and III that are included to the present thesis

| | Study I Estonia | Study II Estonia | Study III Kenya |
|---|---|---|---|
| Sample size | MD = 20<br>LD = 20 | CR = 28<br>RR = 17 | CR = 32 |
| Anthropometry: | | | |
| skinfolds | 6 | 6 | – |
| girths | 13 | 13 | 4 |
| lengths | 8 | 8 | 5 |
| Body composition | Yes | Yes | No |
| Achilles tendon moment arm | No | No | Yes |
| Incremental running test on treadmill | Yes | Yes | Yes |
| 2 x 2 000 m steady-state run test | No | Yes | No |
| Incremental running test on track | No | No | No |
| IAAF performance score (p) | 829 ± 99 (MD)<br>814 ± 85 (LD) | 821 ± 100 (CR)<br>521 ± 132 (RR) | 993 ± 77 (CR) |
| Time 1 500 m (min:s) | 4:02.21 (MD)<br>4:03.50 (LD) | 4:02.90 (CR)<br>4:31.80 (RR) | 3:48.72 (CR) |
| Time in marathon (h:min:s) | 2:30:11 (MD)<br>2:31:11 (LD) | 2:30:43 (CR)<br>2:52:57 (RR) | 2:19:49 (CR) |

Middle-distance runners (MD); long-distance runners (LD); competitive level runners (CR); recreational level runners (RR); corresponding time in 1 500 m run to IAAF performance score (Time 1500 m); corresponding time in marathon run to IAAF performance score (Time in marathon).

## 4.2. Anthropometric and physiological determinants of running performance in Estonian middle- and long-distance runners (I)

### 4.2.1. Participants and study design

A total of 40 male national-level middle- and long-distance runners participated in the study. Athletes were recruited from different training groups across the country and were contacted through e-mail. The runners were classified as middle-distance runners (*N* = 20) when competing from 800 to 1 500 m and long-distance runners (*N* = 20) when competing from 3 000 m to marathon distances based on the highest International Association of Athletics Federations (IAAF) scores during the last season in the corresponding distance (Spiriev, 2011). The 3 000 m distance was used as the cut-off value because it has been shown that $\dot{V}O_{2max}$ values increase from 100 to 3 000 m and plateau for the longer distances (3 000 m to marathon) (Legaz, et al., 2007). The participation criteria were a minimum of five times per week regular training sessions during the last three years, average monthly mileage during the last year at least 240 km and inclusion in the top 20 at National Athletics Association ranking list at least in one distance between 800 m and marathon. The best performance of athletes involved in several events was established using the Scoring Tables of the IAAF (Legaz & Eston, 2005; Spiriev, 2011). Study procedures and protocols were approved by the local ethics committee. All the procedures and possible risks were described and the participants were familiarized with the procedures before providing a written informed consent to participate in the experiment.

A cross-sectional analysis of a total 40 male national level middle- and long-distance runners was performed at the end of the outdoor season. On the first visit to the laboratory, anthropometric parameters and body composition were measured and $\dot{V}O_{2max}$ determined on a motorized treadmill (see specific protocols below). Throughout the study period, athletes were requested to maintain their usual dietary intake, to refrain from alcohol and caffeine ingestion and to abstain from hard training and/or competition for at least 24 h before testing for standardisation purposes and for subjects to be well prepared for the experimental tests.

### 4.2.2. Anthropometry and body composition

Body height (Seca height rod 225, Seca GmbH & Co, Hamburg, Germany) and body mass (A&D Instruments Ltd, Oxfordshire, UK) of the participants were measured to the nearest 0.1 cm and 0.05 kg, respectively. In total, six skinfolds (triceps, subscapular, iliac crest, abdominal, front thigh and medial calf), 13 girths (head, neck, arm relaxed, arm flexed and tensed, forearm, wrist, chest, waist, gluteal, thigh, mid-thigh, calf, ankle), and eight lengths (acromialeradiale, radiale-stylion, midstylion-dactylion, iliospinale height, trochanterion height, trochanterion-tibiale laterale, tibiale-laterale height, tibiale mediale-sphyrion tibiale) were recorded. The sum of six skinfolds (triceps, subscapular, iliac crest, abdominal, front thigh and medial calf) was calculated (Legaz & Eston, 2005; Lucia, et al., 2006). The series of anthropometric measurements were taken by a trained anthropometrist who had previously shown test-retest reliability of $r$ > .90. The Centurion kit (Rosscraft, Surrey, BC, Canada) instrumentation was used for skinfold, girth and length measurements. All anthropometric variables were measured according to the protocol re-commended by the International Society for Advancement of Kinanthropometry (ISAK) (Norton & Olds, 1996). The following calculations were made:

$$upper\ leg\ (thigh)\ length\ =\ iliospinale\ -\ tibiale\ laterale, \quad (1)$$

and

$$total\ leg\ length\ =\ upper\ leg\ (thigh) length\ +\ tibiale\ mediale\ sphyrion\ tibiale\ (lower\ leg\ length). \quad (2)$$

In addition, the following anthropometric ratios were calculated:

$$leg\ mass\ to\ body\ mass\ = \frac{leg\ mass}{body\ mass} \cdot 100; \quad (3)$$

$$upper\ leg\ (thigh)\ mass\ to\ body\ mass\ = \frac{upper\ leg\ (thigh)\ mass}{body\ mass} \cdot 100; \quad (4)$$

$$lower\ leg\ (calf)\ mass\ to\ body\ mass\ = \frac{lower\ leg\ (calf)\ mass}{body\ mass} \cdot 100; \quad (5)$$

$$lower\ leg\ (calf)\ mass\ to\ upper\ leg\ (thigh) mass = \frac{lower\ leg\ (calf)\ mass}{upper\ leg\ (thigh)\ mass} \cdot 100; \quad (6)$$

$$leg\ length\ to\ body\ height\ = \frac{leg\ length}{body\ height} \cdot 100; \quad (7)$$

$$upper\ leg\ (thigh)\ length\ to\ body\ height = \frac{upper\ leg\ (thigh)\ length}{body\ height} \cdot 100; \quad (8)$$

$$lower\ leg\ (calf)\ length\ to\ body\ height = \frac{lower\ leg\ (calf)\ length}{body\ height} \cdot 100; \quad (9)$$

$$lower\ leg\ (calf)\ length\ to\ upper\ leg\ (thigh)\ length = \frac{lower\ leg\ (calf)\ length}{upper\ leg\ (thigh)\ length} \cdot 100. \quad (10)$$

Relative subcutaneous fat patterning was assessed by the distribution of skinfolds on the body (Legaz & Eston, 2005):

$$ET\ ratio = \frac{extremity\ (triceps, front\ thigh, medial\ calf)}{trunk\ (subscapular, iliac\ crest, abdominal)}. \quad (11)$$

Body composition was measured by Dual Energy X-ray Absorptiometry (DXA) (DPX-IQ Lunar Corporation, Madison, WI, USA) with the participant in supine position (Hetland, et al., 1998). Total fat and lean mass were measured for total body, upper leg (thigh) and lower leg (calf).

### 4.2.3. Exercise testing

Following familiarisation with all procedures including treadmill running, participants performed an incremental running test on a motorized treadmill (HP Cosmos Quasar, Nussdorf-Traunstein, Germany) until voluntary exhaustion. The initial treadmill speed was set at 8 $km \cdot h^{-1}$ and was increased by 2 $km \cdot h^{-1}$ after every three minutes up to 14 $km \cdot h^{-1}$. At that point the speed was increased by 1 $km \cdot h^{-1}$ every three minutes until voluntary exhaustion (Zafeiridis, et al., 2010). The treadmill inclination was set at a constant gradient of 1% to simulate outdoor running (Jones & Doust, 1996; Lucia, et al., 2006). Expired gases were measured continuously by the oxygen analyzer Metamax 3B (Cortex Biophysic GMBH, Leipzig, Germany). Metabolic cart was calibrated before each measurement according to the manufacturer's instructions.

$\dot{V}O_{2max}$ was defined as the highest average $\dot{V}O_2$ during a 30 second period and a failure to increase $\dot{V}O_2$ further despite an increase in work rate (Wasserman, et al., 2005). Speed at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$) was defined as the highest treadmill speed at the end of the test. If the runner could not complete the three-minute period of the last speed, the $v\dot{V}O_{2max}$ was calculated using the last completed velocity (vlast) and the relative duration of the last uncompleted velocity (frac) as follows (Kaikkonen, et al., 2010):

$$v\dot{V}O_{2max} = vlast + frac. \quad (12)$$

The VT2 was determined as the second rise in the ventilation and VT2 speed (vVT2) was defined as a corresponding treadmill speed (Rabadan, et al., 2011).

#### 4.2.4. Statistical analysis

Middle- and long-distance groups were compared with Student t-test or Mann-Whitney U-test. Pearson's or Spearman's correlation coefficients were used to determine the correlation between IAAF points and anthropometric and body composition characteristics. The variables that showed statistically significant correlation with the IAAF points were used in linear regression. Binary logistic regression was applied to determine which variables had most influence on the odds of being either a middle-distance or a long-distance runner. Goodness-of-fit tests included model chi-squares to determine model appropriateness and Wald statistics to evaluate the contributions of predictor variables. Finally, using the same variables derived from the binary logistic regressions, discriminant analyses were performed to control a function that would predict the specialty to which an athlete might be best suited. All calculations were performed using SPSS v.17 software for Windows (SPSS Inc., Chicago, IL, USA). The level of significance was set at $p < .05$. Statistical power for significant differences was higher than .82.

## 4.3. Running economy and body composition between Estonian competitive and recreational level distance runners (II)

#### 4.3.1. Participants and study design

A total of 45 male runners were classified as competitive runners ($N = 28$) when belonging to top 20 at the National Athletics Association ranking table at least one distance between 800 m and marathon, and recreational runners ($N = 17$) when not belonging to top 20 at the National Athletics Association ranking table. Participation criteria of the study were regular trainings during the last three years, minimum three times per week and the average monthly mileage during the last year for at least 150 km. The best performance of athletes involved in several events was established using Scoring Tables of the IAAF (Legaz & Eston, 2005; Lucia, et al., 2008; Spiriev, 2011). IAAF tables assign a definite score to each performance, enabling to compare performances in different events (Legaz & Eston, 2005). The study was approved by the University of Tartu ethics committee conformed to the Declaration of Helsinki. All the procedures and possible risks were described and the participants were familiarized with the procedures before providing a written informed consent to participate in the study.

A cross-sectional analysis of a total 45 male distance runners was performed at the end of the outdoor season. On the first visit to the laboratory, anthropometric parameters and body composition were measured and $\dot{V}O_{2max}$ determined on a motorized treadmill (see specific protocols below). At least two days after treadmill test a typical 2 × 2 000 m steady state run test was performed on the indoor track. Throughout the study period, athletes were requested to maintain their usual dietary intake, to refrain from alcohol and caffeine ingestion and to abstain from hard training and/or competition for at least 24 h before testing for standardisation purposes and for subjects to be well prepared for the experimental tests.

### 4.3.2. Anthropometry and body composition

The height (Seca height rod 225, Seca GmbH & Co, Hamburg, Germany) and body mass (A&D Instruments Ltd., Oxfordshire, UK) of the participants were measured to the nearest 0.1 cm and 0.05 kg, respectively. Body composition was measured by Dual Energy X-ray Absorptiometry (DXA) (DPX-IQ Lunar Corporation, Madison, WI, USA). The three compartments (lean, fat and bone) were measured with the participant in the supine position (Hetland, et al., 1998). Total fat and lean mass were measured for total body, upper leg (thigh) and lower leg (calf).

### 4.3.3. Exercise testing: incremental test on treadmill

Following familiarisation with all procedures, including treadmill running, participants performed an incremental running test on a motorized treadmill (HP Cosmos Quasar, Nussdorf-Traunstein, Germany) until voluntary exhaustion. Initial running speed was set on 8 $km \cdot h^{-1}$, gradient 1% (Jones & Doust, 1996; Lucia, et al., 2006) and then increased by 2 $km \cdot h^{-1}$ every three minutes until 14 $km \cdot h^{-1}$. Subsequently speed increased by 1 $km \cdot h^{-1}$ after every three minutes until voluntary exhaustion (Zafeiridis, et al., 2010; Weston, et al., 2000). Expired gases and heart rate (HR) were measured using the Metamax 3B (Cortex Biophysic GmbH, Leipzig, Germany), calibrated before each test according to manufacturer's instructions.

$\dot{V}O_{2max}$ was defined as the highest average $\dot{V}O_2$ during a 30 second period and a failure to increase $\dot{V}O_2$ further despite an increase in work rate (Billat, et al., 2003; Wasserman, et al., 2005). When athletes did not reach a $\dot{V}O_2$ plateau, it was considered to be $\dot{V}O_{2peak}$ rather than $\dot{V}O_{2max}$, however, we used the term $\dot{V}O_{2max}$ for all the athletes for easier reading (Billat, et al., 2003).

Ventilatory threshold 1 (VT1tread) and 2 (VT2tread) were determined as described by Rabadan et al. (2011). VT1tread was determined: (i) as the first exponential increment in ventilation (VE); (ii) as the first rise in the VE–$\dot{V}O_2$ relationship without increments in the VE–$\dot{V}CO_2$ relationship. VT2tread was determined as the second rise in ventilation and as the intensity that accompanied a second rise in the VE–$\dot{V}O_2$ relationship with a concurrent rise in the VE–$\dot{V}CO_2$ relationship. Speeds at ventilatory thresholds (vVT1tread and vVT2tread) were defined as treadmill velocity at the point where the runner reached VT1tread and VT2tread, respectively, and the correspondent heart rate (HR) values were also determined.

### 4.3.4. Exercise testing: in field running test

At least two days after the treadmill test a typical 2 × 2 000 m steady state run test was used on the indoor track (200 m lap). Warm-up consisted of about 10 minutes of low intensity running after which runners stretched for about five minutes and then rested for five minutes. The intensity of the first run was at VT1, and the intensity of the second run was at VT2. Participants were instructed to run at the same target HR since it has been shown that there are no significant differences between HR curves when running on treadmill or indoor track (Meyer, et al., 2003). Recovery time between two runs was two minutes. During recovery, runners walked slowly on the track. HR and expired gases were measured continuously throughout the test by Metamax 3B (Cortex Biophysic GMBH, Leipzig, Germany). RE was measured during the last two minutes on both 2 000 m runs at indoor track and was expressed as ($O_2$ ml·kg$^{-1}$·km$^{-1}$) and was calculated as follows:

$$RE = \frac{1000 \cdot \dot{V}O_2}{v}, \quad (13)$$

where $\dot{V}O_2$ is a steady-state oxygen uptake (ml·kg$^{-1}$·min$^{-1}$) and v is a running velocity (m·min$^{-1}$) (Bragada, et al., 2010). Steady-state $\dot{V}O_2$ was defined as an increase of less than 100 ml $O_2$ over the final two minutes of each stage (Fletcher, et al., 2009).

### 4.3.5. Statistical analysis

Competitive and recreational runners were compared with Student t-test or Mann-Whitney U test. Pearson's or Spearman's, where necessary, correlation coefficient was used to determine the correlation between RE and body composition parameters. All calculations were performed using SPSS v.17 software for Windows (SPSS Inc., Chicago, IL, USA). The level of significance was set at $p < .05$.

## 4.4. Dissociation between running economy and running performance in national level Kenyan distance runners (III)

### 4.4.1. Participants and study design

A total of 32 competitive male Kenyan runners, competing in different distances between 1500 m up to the marathon, were recruited to this study. All athletes competed in various distances, however, the distance with best performance of the ongoing season, established using the IAAF Scoring Tables (Legaz & Eston, 2005; Lucia, et al., 2008; Spiriev, 2011), was included to the analysis. These tables assign a definite score to each performance, enabling comparison between events (Legaz & Eston, 2005). Study procedures and protocols were approved by the Ethics Committee of Moi University (Kenya) and University of Glasgow (Scotland, UK) and conformed to the Declaration of Helsinki. All testing procedures and related risks were described and participants well familiarized with these procedures before providing written informed consent to participate in the overall study.

A cross-sectional analysis of a total 32 male Kenyan runners was performed at altitude (2 200 m a.s.l) in Eldoret, Kenya. On the first visit to the laboratory, anthropometric parameters were measured and $\dot{V}O_{2max}$ determined on a motorized treadmill (see specific protocols below). Throughout the study period, athletes were requested to maintain their usual dietary intake, to refrain from alcohol and caffeine ingestion and to abstain from hard training and/or competition for at least 24 h before testing for standardisation purposes and for subjects to be well prepared for the experimental tests.

### 4.4.2. Anthropometry

The height (Seca height rod 225, Seca GmbH & Co, Hamburg, Germany) and body mass (Salter 144SVBKDR, Salter Houseware Ltd., United Kingdom) of the participants were measured to the nearest 0.1 cm and 0.1 kg, respectively. In total, four girths and five lengths were measured using the Centurion Kit instrumentation (Rosscraft, Surrey, BC, Canada) according to protocols recommended by the International Society for Advancement of Kinanthropometry (Norton & Olds, 1996). Upper leg (thigh) length and total leg length were calculated according to Equation 1 and 2.

The Achilles tendon moment arm was determined as well described and validated by Scholz et al. (2008). In summary, the Achilles tendon moment arm represents the mean of the lateral and medial horizontal distances from the most prominent tip of the *malleoulus* to the posterior aspect of the Achilles tendon while subject is seated with knee and ankle at 90 degrees (Scholz, et al., 2008). The measured foot is placed on a reference block with firstly the lateral followed by medial side of the foot aligned with the tape measure on the reference block. The vertical position of the *tibia* is corrected with a spirit level.

The lateral and medial *malleoulus* are marked on the most prominent aspect with white corrector paint. The right foot is photographed (Canon Digital Camera, IXUS-130, Canon Ltd. Woodhatch, Reigate, Surrey, United Kingdom) from the lateral and medial side and distances determined on the photographs using Cell A Soft Imaging System Software (Olympus Soft Imaging Solution GmbH, Münster, Germany). The high inter- and intra-observer reliability ($R^2 > .95$, $p < .001$) of this precise method has been established by Scholz et al. (2008) by comparing two measurements made by the same person several months apart. Furthermore the digital photographic measurements method was reported to be a valid and reliable clinical and research tool for quantifying foot structure by Cobb et al. (2011).

### 4.4.3. Exercise testing

Following familiarisation with all procedures including treadmill running, participants performed an incremental running test on a motorized treadmill (Cardionics Type 3113, Sweden) until voluntary exhaustion. Before commencement of the exercise test, each athlete remained stationary on the treadmill for three minutes and cardio-respiratory data was recorded. Initial running speed was set on 8 $km \cdot h^{-1}$, gradient 1% (Jones & Doust, 1996; Lucia, et al., 2006) and then increased by 2 $km \cdot h^{-1}$ every three minutes until 16 $km \cdot h^{-1}$. Following three minutes at 17 $km \cdot h^{-1}$, the speed remained constant at 17 $km \cdot h^{-1}$ and elevation increased 1% after every one minute until voluntary exhaustion. Expired gases and HR were measured using the Metamax 3B (Cortex Biophysic GmbH, Leipzig, Germany), calibrated before each test according to manufacturer's instructions.

RE was expressed as steady state oxygen uptake during the last two minutes of the 16 $km \cdot h^{-1}$ treadmill bout. Steady-state $\dot{V}O_2$ was defined as an increase of less than 100 ml $O_2$ over the final two minutes of each stage (Fletcher, et al., 2009). $\dot{V}O_{2max}$ was defined as the highest average $\dot{V}O_2$ during 30 second period and failure to increase $\dot{V}O_2$ further despite an increase in work rate. When participants did not reach a $\dot{V}O_2$ plateau, we considered that it was a $\dot{V}O_{2peak}$ rather than $\dot{V}O_{2max}$. However, for an easier reading, we have used the acronym $\dot{V}O_{2max}$ for all the subjects (Billat, et al., 2003).

### 4.4.4. Statistical analysis

Pearson's or Spearman's correlation coefficients, where necessary, were used to assess the correlation between the IAAF performance score and respective anthropometric characteristics and also between RE and anthropometric characteristics. Partial correlation was also used to test and correct for anthropometric variables that covaried with the Achilles tendon moment arm as previously described (Scholz, et al., 2008).

The relationship between the Achilles tendon moment arm and RE was also assessed using a non-linear model of the form $y = ax^{-2} + c$ (Scholz, et al., 2008). Interobserver reliability for the determination of Achilles tendon moment arm from pictures of the ankle was assessed by comparing two measurements made by different researchers, using Bland and Altman method (Bland & Altman, 1986). Calculations were performed using SPSS v.17 software for Windows (SPSS Inc., Chicago, IL, USA) and G*Power v 3.1.5.1 (G*Power, Düsseldorf, Germany). The level of significance was set at $p < .05$.

# 5. RESULTS

## 5.1. Anthropometric and physiological determinants of running performance in Estonian middle- and long-distance runners (I)

Long-distance runners showed significantly higher VT2 and $\dot{V}O_{2max}$ speeds than middle-distance runners when running on a treadmill (Table 2). The long-distance runners were significantly older than the middle-distance runners. However, the two groups of runners did not differ significantly according to their body mass.

**Table 2.** Characteristics of the middle-distance (MD) and long-distance (LD) runners (mean ± *SD*)

| | MD ($N = 20$) | LD ($N = 20$) |
|---|---|---|
| Age (y) | 21.1 ± 3.4 | 25.4 ± 3.8** |
| Height (m) | 1.80 ± 0.04 | 1.81 ± 0.05 |
| Body mass (kg) | 70.5 ± 6.3 | 69.0 ± 4.5 |
| BMI ($kg \cdot m^{-2}$) | 21.6 ± 1.5 | 21.1 ± 1.2 |
| Body fat (%) | 8.1 ± 2.0 | 7.6 ± 1.9 |
| IAAF performance score (p) | 829 ± 99 | 814 ± 85 |
| $\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) | 64.2 ± 5.8 | 67.4 ± 5.9 |
| $v\dot{V}O_{2max}$ ($km \cdot h^{-1}$) | 17.8 ± 1.3 | 19.0 ± 1.0** |
| vVT2 ($km \cdot h^{-1}$) | 16.4 ± 1.3 | 17.3 ± 0.8* |

Body mass index (BMI); maximal oxygen uptake ($\dot{V}O_{2max}$); treadmill speed at maximal oxygen uptake intensity ($v\dot{V}O_{2max}$); treadmill speed at second ventilatory threshold intensity (vVT2); significant differences between middle-distance and long-distance runners (* $p < .05$; ** $p < .01$).

Running performance (IAAF performance score) of long-distance runners was significantly related to the maximal running time on a treadmill ($t_{max}$) ($r = .63$; $p = .005$). Of the physiological parameters only VT2 time was significantly related ($r = .57$; $p = .021$) to performance in middle-distance runners.

Middle- and long-distance runners did not differ significantly in values for the measured skinfolds, circumferences and lengths (Table 3). The only exception was lower leg length which was significantly longer in the middle-distance runners. The studied groups did not differ significantly in total body, upper and lower leg fat mass and fat-free mass.

**Table 3.** Anthropometric and body composition parameters in middle-distance (MD) and long-distance (LD) runners (mean ± *SD*)

| | MD (*N* = 20) | LD (*N* = 20) |
|---|---|---|
| **Skinfolds** | | |
| Triceps (mm) | 5.4 ± 1.9 | 4.3 ± 1.4 |
| Subscapular (mm) | 6.6 ± 0.9 | 6.0 ± 1.3 |
| Iliac crest (mm) | 7.0 ± 2.2 | 6.3 ± 1.0 |
| Abdominal (mm) | 7.6 ± 2.4 | 6.1 ± 1.7 |
| Front thigh (mm) | 6.3 ± 1.8 | 6.9 ± 2.2 |
| Medial calf (mm) | 4.1 ± 2.2 | 4.0 ± 2.5 |
| Sum of 6 skinfolds (mm) | 35.5 ± 8.3 | 33.4 ± 7.6 |
| **Circumferences** | | |
| Arm (relaxed) (cm) | 27.6 ± 1.8 | 26.5 ± 1.8 |
| Waist (cm) | 75.1 ± 3.2 | 74.3 ± 3.0 |
| Upper leg (cm) | 53.1 ± 2.7 | 51.8 ± 1.4 |
| Mid-thigh (cm) | 50.9 ± 2.9 | 49.5 ± 1.6 |
| Lower leg (cm) | 37.3 ± 1.7 | 36.4 ± 1.2 |
| Ankle (cm) | 24.6 ± 3.4 | 22.8 ± 0.9 |
| **Lengths** | | |
| Total leg length (cm) | 92.7 ± 4.1 | 89.3 ± 5.7 |
| Upper leg (thigh) length (cm) | 52.5 ± 2.9 | 51.3 ± 3.6 |
| Lower leg (calf) length (cm) | 39.9 ± 2.1 | 38.0 ± 2.5* |
| **Body composition** | | |
| Total fat mass (kg) | 5.8 ± 1.6 | 5.3 ± 1.3 |
| Body lean mass (kg) | 61.9 ± 5.3 | 60.2 ± 6.1 |
| Upper leg fat mass (kg) | 1.5 ± 0.5 | 1.2 ± 0.5 |
| Upper leg fat (%) | 13.1 ± 4.4 | 10.8 ± 3.8 |
| Upper leg lean mass (kg) | 9.4 ± 1.1 | 9.5 ± 0.8 |
| Upper leg total mass (kg) | 11.3 ± 1.2 | 11.2 ± 1.0 |
| Lower leg fat mass (kg) | 0.3 ± 0.2 | 0.3 ± 0.1 |
| Lower leg fat (%) | 6.6 ± 3.0 | 5.7 ± 2.2 |
| Lower leg lean mass (kg) | 3.7 ± 0.3 | 3.7 ± 0.3 |
| Lower leg total mass (kg) | 4.4 ± 0.4 | 4.2 ± 0.3 |
| Total leg mass (kg) | 15.7 ± 1.4 | 15.4 ± 1.2 |

Significant differences between middle-distance and long-distance runners (* $p < .05$).

Correlation analysis showed that the running performance (IAAF performance score) in middle-distance runners was significantly related to lower leg mass to upper leg mass ratio ($r$ = .67; $p$ = .003) and total body lean mass ($r$ = .61; $p$ = .010) from the anthropometric and body composition parameters. All other relationships between the running performance and the measured variables were not significant in middle-distance runners. In contrast, there were no parameters from the measured and calculated anthropometric and body composition variables that were significantly related to running performance in long-distance runners.

From the calculated length ratios, only lower leg to body length ratio (Table 4) differentiated significantly between the middle- and long-distance runners. However, there were no differences in body mass ratios between the middle- and long-distance runners. In the long-distance group, upper leg to body length ratio was correlated with performance ($r$ = .59; $p$ = .042).

**Table 4.** Mass and length ratios between middle-distance (MD) and long-distance (LD) runners (mean ± *SD*)

| | MD (*N* = 20) | LD (*N* = 20) |
|---|---|---|
| **Mass ratios** | | |
| Leg to body mass (%) | 22.3 ± 0.5 | 22.4 ± 0.9 |
| Upper leg to body mass (%) | 16.0 ± 0.5 | 16.1 ± 0.9 |
| Lower leg to body mass (%) | 6.2 ± 0.5 | 6.1 ± 0.3 |
| Lower leg to upper leg mass (%) | 39.0 ± 3.6 | 38.1 ± 2.7 |
| **Length ratios** | | |
| Leg length to body height (%) | 51.1 ± 1.7 | 49.7 ± 2.3 |
| Upper leg length to body height (%) | 28.9 ± 1.3 | 28.6 ± 1.6 |
| Lower leg length to body height (%) | 22.0 ± 0.9 | 21.2 ± 1.0* |
| Lower leg length to upper leg length (%) | 76.7 ± 3.9 | 74.3 ± 3.6 |
| **Skinfold ratio** | | |
| E/T ratio | 0.77 ± 0.21 | 0.82 ± 0.24 |

Extremity (*triceps, front thigh, medial calf*)/trunk (*subscapular, iliac crest, abdominal*) skinfold ratio (E/T ratio); significant differences between middle-distance and long-distance runners (* $p < .05$).

Linear regression analyses indicated that the anthropometric variables ($Adj\ R^2 = .41$) predicted running performance better than the physiological variables ($Adj\ R^2 = .33$) in middle-distance runners (Table 5). Therefore, lower leg mass to upper leg mass ratio appeared to be the best predictor of running performance in middle-distance runners. However, the total time on a treadmill characterized 36% of the variance in running performance in long-distance runners, while there were no anthropometric parameters or indices to predict the running performance in long-distance runners (Table 5).

**Table 5.** Results of linear regressions to predict middle-distance (MD) and long-distance (LD) performance (IAAF points)

**Middle-distance**

| Model 1 | *B* | *SE* | β | *t* | *p* |
|---|---|---|---|---|---|
| Lower leg/upper leg mass (%) | –18.69 | 5.38 | –0.67 | –3.48 | .003 |
| *Constant* | 1547.62 | 210.47 | | 7.35 | .000 |
| $R^2$ | .45 | | | | |
| *Adj* $R^2$ | .41 | | | | |
| *SE* | 77.71 | | | | |
| $F(df_n,df_d)$ | 12.08 | | | | |

| Model 2 | *B* | *SE* | β | *t* | *p* |
|---|---|---|---|---|---|
| VT2time (s) | 0.20 | 0.08 | 0.57 | 2.60 | .021 |
| *Constant* | 631.41 | 79.90 | | 7.90 | .000 |
| $R^2$ | .57 | | | | |
| *Adj* $R^2$ | .33 | | | | |
| *SE* | 73.57 | | | | |
| $F(df_n,df_d)$ | 6.73 | | | | |

**Long-distance**

| Model 1 | *B* | *SE* | β | *t* | *p* |
|---|---|---|---|---|---|
| $t_{max}$ (s) | 0.41 | 0.13 | 0.63 | 3.27 | .005 |
| *Constant* | 162.30 | 202.54 | | 0.80 | .435 |
| $R^2$ | .40 | | | | |
| *Adj* $R^2$ | .36 | | | | |
| *SE* | 66.20 | | | | |
| $F(df_n,df_d)$ | 10.69 | | | | |

Second ventilatory threshold time (VT2time); maximal running time on treadmill ($t_{max}$).

Subsequently binary logistic regression was used to find out which indices were important to categorize athletes as either middle- or long-distance runners. The constructed model showed that $\dot{V}O_{2max}$ time (*OR* = 1.01, 95% *CI* 1.01−1.01) and age (*OR* = 1.57; 95% *CI* 1.07−2.31) classified athletes in their specialties. The following discriminant analyses confirmed that these variables were sufficient to produce a function that would predict the specialty of athletes (Wilks' $\lambda = .61$; $\chi^2 = 15.17$; $p = .001$).

## 5.2. Running economy and body composition between Estonian competitive and recreational level distance runners (II)

Descriptive parameters of the participants and their performance at the VT1 and VT2 intensities on track (VT1track and VT2track, respectively) are presented in Table 6. Competitive and recreational level runners showed similar RE values at their individual thresholds but the corresponding speed at VT2track was significantly higher for the competitive level runners group.

**Table 6.** Characteristics of the participants (mean ± *SD*)

| | CR ($N = 28$) | RR ($N = 17$) |
|---|---|---|
| Age (y) | 23.0 ± 4.4 | 25.5 ± 8.3 |
| Height (m) | 1.81 ± 0.05 | 1.78 ± 0.06 |
| Body mass (kg) | 69.3 ± 5.5 | 70.6 ± 7.7 |
| BMI (kg·min$^{-2}$) | 21.2 ± 1.1 | 22.2 ± 2.1 |
| Body fat (%) | 7.3 ± 1.6 | 10.3 ± 4.5$^{*}$ |
| IAAF performance score (p) | 821 ± 100 | 521 ± 132$^{*}$ |
| $\dot{V}O_{2max}$ (ml·min$^{-1}$·kg$^{-1}$) | 67.1 ± 5.6 | 63.8 ± 4.2$^{*}$ |
| **VT1track** | | |
| $\dot{V}O_2$ (ml·min$^{-1}$·kg$^{-1}$) | 50.6 ± 7.4 | 46.6 ± 5.4 |
| t (s) | 566 ± 118 | 597 ± 74 |
| RE ($O_2$ ml·kg$^{-1}$·km$^{-1}$) | 232 ± 242 | 230 ± 26 |
| v (m·s$^{-1}$) | 3.65 ± 0.55 | 3.40 ± 0.40 |
| **VT2track** | | |
| $\dot{V}O_2$ (ml·min$^{-1}$·kg$^{-1}$) | 61.9 ± 8.2 | 57.3 ± 5.8 |
| t (s) | 462 ± 79 | 492 ± 61$^{*}$ |
| RE ($O_2$ ml·kg$^{-1}$·km$^{-1}$) | 233 ± 17 | 234 ± 15 |
| v (m·s$^{-1}$) | 4.42 ± 0.55 | 4.12 ± 0.45$^{*}$ |

Competitive level runners (CR); recreational level runners (RR); body mass index (BMI); maximal oxygen uptake ($\dot{V}O_{2max}$); oxygen uptake ($\dot{V}O_2$); time (t); running economy (RE); speed (v); significantly different from competitive level runners (* $p < .05$).

**Table 7.** Body composition and mass ratios (mean ± *SD*)

| | CR ($N = 28$) | RR ($N = 17$) |
|---|---|---|
| **Body composition** | | |
| Total body fat mass (kg) | 5.14 ± 1.28 | 7.59 ± 3.82* |
| Total body lean mass (kg) | 61.05 ± 6.24 | 60.72 ± 5.40 |
| Upper leg fat mass (kg) | 1.22 ± 0.43 | 1.78 ± 1.01* |
| Upper leg fat (%) | 10.99 ± 3.85 | 14.94 ± 7.43 |
| Upper leg lean mass (kg) | 9.43 ± 1.02 | 9.34 ± 1.05 |
| Upper leg total mass (kg) | 11.11 ± 1.10 | 11.31 ± 1.14 |
| Lower leg fat mass (kg) | 0.28 ± 0.14 | 0.35 ± 0.18 |
| Lower leg fat (%) | 6.28 ± 2.83 | 7.88 ± 3.83 |
| Lower leg lean mass (kg) | 3.72 ± 0.27 | 3.65 ± 0.31 |
| Lower leg total mass (kg) | 4.35 ± 0.36 | 4.28 ± 0.30 |
| Total leg total mass (kg) | 15.46 ± 1.37 | 15.60 ± 1.36 |
| **Mass ratios** | | |
| Leg to body mass (%) | 22.3 ± 0.7 | 22.4 ± 0.8 |
| Upper leg to body mass (%) | 15.9 ± 0.6 | 16.1 ± 0.6 |
| Lower leg to body mass (%) | 6.3 ± 0.4 | 6.2 ± 0.4 |
| Lower leg to upper leg mass (%) | 39.3 ± 3.2 | 37.9 ± 3.1 |

Competitive level runners (CR); recreational level runners (RR); significantly different from competitive level runners (* $p < .05$).

Significant differences between competitive and recreational runners body composition parameters are presented in Table 7. As seen in Table 6 and 7, there is high variability in recreational runners' body composition parameters. Lean body mass was significantly correlated with RE at VT2track only in recreational athletes ($r = -.54$; $p = .045$), indicating that runners with better RE have significantly higher lean body mass. RE at VT1track in competitive and recreational runners was not significantly related to any of the measured body composition values. The other relationships between RE and measured body composition parameters and body mass ratios were not statistically significant.

## 5.3. Dissociation between running economy and running performance in national level Kenyan distance runners (III)

The main characteristics of national level Kenyan distance runners are presented in Table 8. Runners were classified as being of very low body mass, BMI and high performance level according to the IAAF performance score and $\dot{V}O_{2max}$ values.

**Table 8.** Characteristics of the participants (mean ± *SD*)

| | Kenyans ($N = 32$) |
|---|---|
| Age (y) | 25.3 ± 5.0 |
| Body mass (kg) | 56.5 ± 5.7 |
| Height (m) | 1.72 ± 0.07 |
| BMI ($kg \cdot m^{-2}$) | 19.0 ± 1.3 |
| IAAF performance score (p) | 993 ± 77 |
| $\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) | 68.8 ± 3.8 |
| $\dot{V}O_2 16$ ($ml \cdot kg^{-1} \cdot min^{-1}$) | 61.0 ± 3.6 |
| **Lengths** | |
| Achilles tendon moment arm (cm) | 4.00 ± 0.43 |
| Tibiale-laterale (cm) | 50.6 ± 2.9 |
| Trochanterion (cm) | 93.1 ± 4.6 |
| Iliospinale (cm) | 101.4 ± 5.0 |
| Lower leg (cm) | 39.4 ± 2.4 |
| Upper leg (cm) | 50.7 ± 2.9 |
| Total leg (cm) | 90.1 ± 4.9 |
| Foot (cm) | 26.3 ± 1.4 |
| **Length ratios** | |
| Lower to upper leg length (%) | 77.7 ± 3.5 |
| Lower leg to body height (%) | 22.8 ± 0.8 |
| Upper leg to body height (%) | 29.4 ± 1.2 |
| Total leg to body height (%) | 52.1 ± 1.7 |
| **Circumferences** | |
| Thigh (cm) | 49.2 ± 2.6 |
| Mid-thigh (cm) | 47.1 ± 2.3 |
| Calf (cm) | 33.6 ± 2.7 |
| Ankle (cm) | 20.3 ± 1.4 |

Body mass index (BMI); maximal oxygen uptake ($\dot{V}O_{2max}$); oxygen uptake at the speed of 16 $km \cdot h^{-1}$ ($\dot{V}O_2 16$).

The Achilles tendon moment arm was strongly correlated ($p = .004$) with RE at the speed of 16 $km \cdot h^{-1}$ in national level Kenyan distance runners, with moment arm explaining 28% of the variance in RE. The non-linear model fitted the data slightly better ($p = .003$) than the linear one (Pearson correlation) and accounted for 30% of the variance in RE (Figure 1).

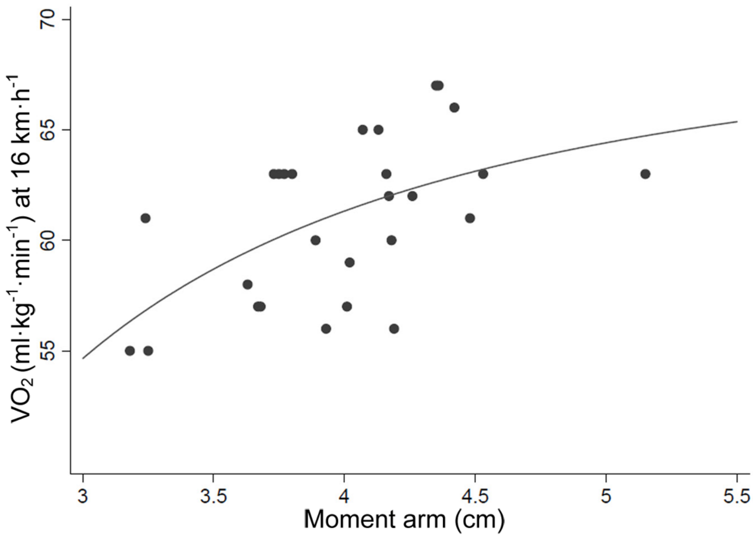


**Figure 1.** Relationship between Achilles tendon moment arm and oxygen uptake ($\dot{V}O_2$) in ml·kg$^{-1}$·min$^{-1}$ at 16 km·h$^{-1}$. The line is the best fit for the theoretical model $y = ax^{-2} + c$, where $x$ is Achilles tendon moment arm in cm and $y$ is $\dot{V}O_2$ in ml·kg$^{-1}$·min$^{-1}$ at 16 km·h$^{-1}$ ($a = -137.19$, $c = 69.88$, $r = .55$, $p = .003$).

Besides the high correlation with moment arm, there were also significant association between RE and BMI, mid-thigh and ankle circumferences ($r = .49$, $p = .010$; $r = .56$, $p = .002$ and $r = .44$, $p = .021$, respectively). Partial correlation revealed that these relationships were no longer significant after controlling for moment arm (Table 9). The correlation between RE and moment arm diminished when controlling for other variables (BMI, mid-thigh and ankle circumference) (Table 10).

**Table 9.** Partial correlations between selected anthropometric variables and RE at 16 km·h$^{-1}$, corrected for covariance with moment arm (in parentheses) in Kenyans ($N = 32$)

| Anthropometric variable | $R^2$ | $p$ |
|---|---|---|
| BMI (moment arm) | .08 | .166 |
| Mid-thigh (moment arm) | .09 | .127 |
| Ankle (moment arm) | .04 | .326 |

Body mass index (BMI); explained variance ($R^2$).

**Table 10.** Partial correlations between moment arm and RE at 16 km·h$^{-1}$, corrected for covariance with selected anthropometric variables (in parentheses) in Kenyans ($N$ = 32)

| Anthropometric variable | $R^2$ | $p$ |
|---|---|---|
| Moment arm (BMI) | .13 | .069 |
| Moment arm (mid-thigh) | .05 | .264 |
| Moment arm (ankle) | .14 | .057 |

Body mass index (BMI); explained variance ($R^2$).

Running performance on the other hand, showed significant relation with upper leg length, total leg length and total leg length to body height ratio ($r$ = .42, $p$ = .025; $r$ = .40, $p$ = .030 and $r$ = .38, $p$ = .043, respectively) (Figure 2). RE was significantly related with $\dot{V}O_{2max}$ ($r$ = .46; $p$ = .017) but not with running performance ($r$ = –.01; $p$ = .959) (Figure 3). Furthermore, $\dot{V}O_{2max}$ was not related with running performance ($r$ = .29; $p$ = .144) or any of the anthropometrical parameters. Maximal running time on treadmill ($t_{max}$) was moderately associated with $\dot{V}O_{2max}$ ($r$ = 0.49; $p$ = .011) but neither with running performance ($r$ = 0.27; $p$ = .189) nor RE ($r$ = –0.25; $p$ = .213).

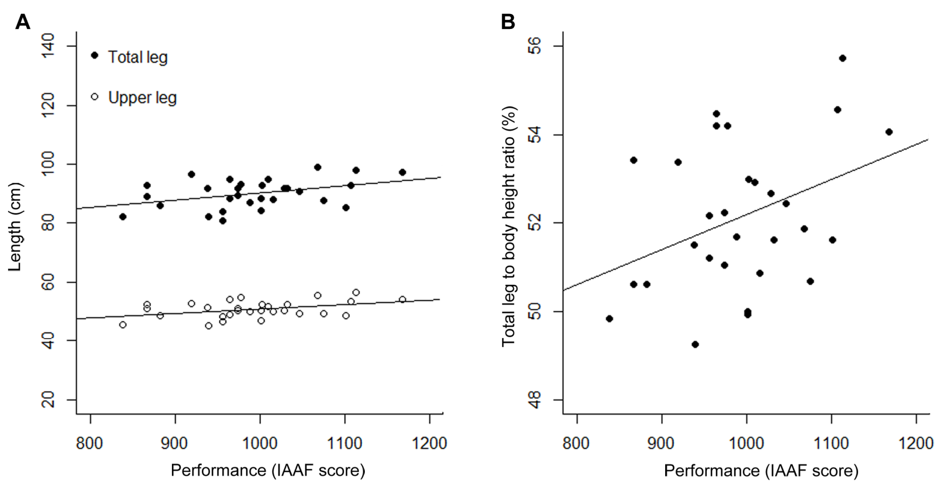


**Figure 2.** Relationship between IAAF performance score and leg anthropometrics. Black and white circles represent relationship between IAAF performance scores and total leg length ($R^2$ = .16; $p$ = .030) and upper leg length ($R^2$ = .17; $p$ = .025) respectively (A). Relationship between IAAF performance score and total leg to body height ratio ($R^2$ = 0.14; $p$ = .043) (B).

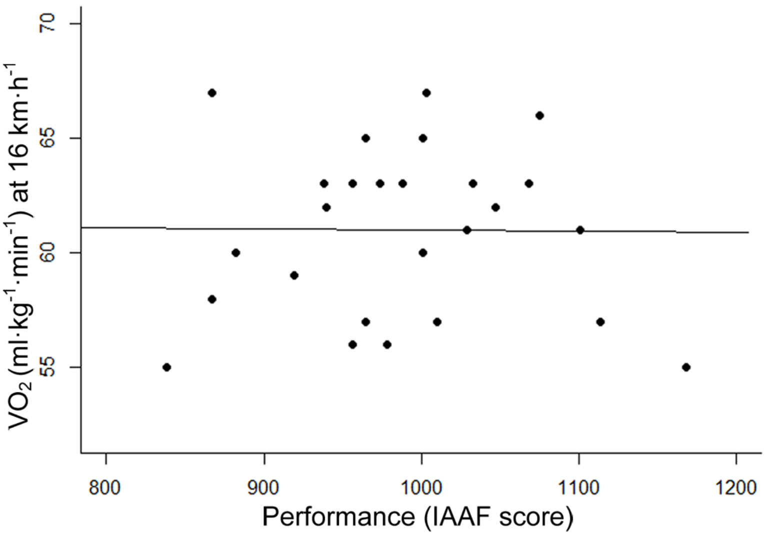


**Figure 3.** Relationship between IAAF performance score and oxygen consumption rate ($\dot{V}O_2$) in ml·kg$^{-1}$·min$^{-1}$ at 16 km·h$^{-1}$ ($R^2$ = .00; $p$ = .959).

# 6. DISCUSSION

## 6.1. Primary findings

The main findings in the present study were as follows:

1. While running performance in middle-distance runners was positively related to lower leg mass to upper leg mass ratio and total body lean mass, $t_{max}$ was related with long-distance performance in national level Estonian runners (Study I).
2. Estonian competitive and recreational level runners have similar RE values at their individual thresholds on running track. Corresponding speed at VT2 on track is significantly higher for competitive level runners (Study II).
3. RE in Estonian competitive and recreational level runners cannot be explained by body composition and/or different leg mass ratios (Study II).
4. RE of national level Kenyan distance runners is related with BMI, mid-thigh and ankle circumferences. Running performance is related with upper leg length, total leg length and total leg length to body height ratio. National level Kenyan runners Achilles tendon moment arm explains 30% of the variance in RE (Study III).
5. RE of homogenous group national level Kenyan distance runners is not related with running performance (Study III).

## 6.2. Anthropometric and physiological determinants of running performance in Estonian middle- and long-distance runners (I)

This study was done to determine and compare the specific anthropometric and body composition parameters together with the selected physiological values that were hypothesized to predict the probability of being either a middle- or a long-distance runner.

In this study there were no significant differences between the middle- and long-distance runners in the overall performance level (IAAF performance score) and the $\dot{V}O_{2max}$ values. The athletes showed $\dot{V}O_{2max}$ values (middle-distance runners: 64.2±5.8 $ml \cdot kg^{-1} \cdot min^{-1}$; long-distance runners: 67.4 ± 5.9 $ml \cdot kg^{-1} \cdot min^{-1}$) similar to those in earlier studies in well-trained Caucasian and African runners (Esteve-Lanao, et al., 2007; Legaz, et al., 2007; Weston, et al., 2000). Previous studies have shown differences between $\dot{V}O_{2max}$ values of middle- and long-distance runners in elite Caucasian athletes (Legaz, et al., 2007; Maldonado, et al., 2002; Rabadan, et al., 2011) with $\dot{V}O_{2max}$ higher in long-distance than in middle-distance runners. The average $\dot{V}O_{2max}$ of the same performance level elite runners from 3 000 m to marathon was not different, thus indicating similar importance of $\dot{V}O_{2max}$ for these running events (Legaz, et al., 2007). However, distances from 100 to 3 000 m indicated different contributions of

$\dot{V}O_{2max}$ to running performance (Legaz, et al., 2007). The athletes in the present study were not world elite runners and therefore their specialization for middle- and long-distance running was not so definite. It can be suggested that $\dot{V}O_{2max}$ values do not differ significantly in national level middle- and long-distance runners with the same body height, body mass, body fat percentage and performance level.

In our study, the speed corresponding to $\dot{V}O_{2max}$ and VT2 (v$\dot{V}O_{2max}$, vVT2) was significantly lower in middle-distance than in long-distance runners. This is in line with an earlier study that indicated significantly lower v$\dot{V}O_{2max}$ in middle-distance runners compared to long-distance runners (Rabadan, et al., 2011). On the one hand, the difference in v$\dot{V}O_{2max}$ can be due to our testing protocol, which consisted of three minutes running stages and thus was more suitable for long-distance runners. On the other hand, long-distance runners train at higher training volumes and therefore they have better aerobic performance compared with middle-distance runners (Rabadan, et al., 2011). Competitions for middle-distance runners last up to around four minutes, while the performance time in long-distance runners starts at around eight and a half minutes. The long-distance runners in the current study reached their VT2 and $\dot{V}O_{2max}$ at 19:30±1:53 (min:s) and 24:25±2:59 (min:s), respectively; while the middle-distance did the same at 16:46±4:05 (min:s) and 21:00±3:45 (min:s), respectively. An earlier study has shown that running speed at the anaerobic threshold was closely related to the running speed over 5 000 m distance and above but no such relationship was found for shorter distances (Maffulli, et al., 1991).

To the best of our knowledge, very few studies have calculated different leg masses and length ratios to find out which of these characterize running performance better in middle- and long-distance runners, and whether the same performance level middle- and long-distance runners can be distinguished according to these ratios. From the calculated leg mass and length ratios only lower leg to body height ratio was different in middle- and long-distance groups (see Table 4). At the same time, lower leg mass to upper leg mass ratio correlated with the running performance in middle-distance ($r = -.67$; $p = .003$) but not in the long-distance group. Previously, it has been hypothesized that runners with a proportionally smaller amount of body mass concentrated in the extremities, particularly in the legs, would perform less work moving their body segments during running, assuming that all other factors were similar (Myers & Steudel, 1985). Myers and Steudel (1985) showed that adding a few grams of mass on the feet/ankle evokes an increase in the metabolic rate. Earlier, it has been explained that increased metabolic rate might be caused by the forward and backward movement of limbs relative to the center of mass. Therefore, added load to the limbs would increase both the total mass to be carried and mechanical energy expended in raising and accelerating the center of mass and in oscillations in kinetic energy of the limbs relative to the center of mass. In addition, it has been shown that a given mass added to subject's limbs causes 1.5 up to 5.5 times higher energy cost than if same amount of mass were added to the subject's center of mass (Myers & Steudel, 1985). Therefore, leg mass and the distribution of mass in legs might be important characteristics in the performance of runners (Kong & de Heer, 2008; Larsen, 2003). The present study showed that lighter lower leg in relation to upper leg was related to performance in middle-distance runners but no such relationship was found in long-distance runners. These discrepancies between the middle- and long-distance runners remain unclear. Reducing body mass and leg mass in particularly, is ought to enhance running performance as a consequence of reducing the kinetic energy required to accelerate and decelerate the limbs (Fudge, et al., 2006). An average increment in $O_2$ by 0.7−1% per 100 g weight added to the footwear has been found earlier (Jones, et al., 1986).

Accordingly, our results demonstrate that the performance variation in the long-distance running group was best described by the total time on a treadmill. Surprisingly, neither the anthropometric nor body composition parameters accounted for significant variance in the long-distance running performance. Lower leg mass to upper leg mass ratio described 41% of the variance in the performance in middle-distance runners, while the VT2 time described only 33% of their running performance. Accordingly, it can be concluded that the lower leg mass to upper leg mass ratio describes the performance of middle-distance runners better than the physiological parameters. One explanation could be that the middle-distance performance has a higher anaerobic energy contribution than the long-distance performance. However this remains unclear at present.

The constructed model showed that the odds of belonging to the long-distance group were higher if an athlete was older and the $\dot{V}O_{2max}$ time increased. One additional year increases the odds of belonging to the long-distance group by 57% when the athletes have the same $\dot{V}O_{2max}$ values. The athletes of the same age have 1% greater odds of belonging to long-distance group when $\dot{V}O_{2max}$ time increases by one second. At the beginning of their running career the athletes start with middle-distance events and later move to the long- distance events. However elite-level middle-distance athletes do not tend to go from middle-distance to long-distance events but it can be the case in national level athletes.

It is important to note that the limitation of this study was the performance level of the investigated athletes, therefore the results of the study are applicable to national level runners only. Low performance level of the athletes can be reason why there was a lack of significant anthropometric differences between the studied groups. On the other hand, it is one of a few studies in which both the middle- and the long-distance runners are at the same performance level (IAAF performance score), thus allowing for their physiological and anthropometric parameters to be compared.

In summary, the results of the present study indicate the importance of specific anthropometric parameters for the prediction of the middle-distance but not the long-distance running performance in well-trained national level athletes with relatively high $\dot{V}O_{2max}$ values. According to the results it can be suggested that national level middle- and long-distance runners of even performance level and with no significant differences in anthropometric and/or body composition characteristics also present similar values for $\dot{V}O_{2max}$. In addition, age and $\dot{V}O_{2max}$ time are important parameters to classify athletes as either middle- or long-distance runners.

## 6.3. Running economy and body composition between Estonian competitive and recreational level distance runners (II)

Running economy at individual ventilatory thresholds in field conditions were compared between competitive and recreational level athletes. In addition, different body composition parameters that are related to the individual RE were compared in competitive and recreational distance runners.

In competitive runners, body fat percent (Billat, et al., 2003; Fudge, et al., 2006) and $\dot{V}O_{2max}$ values (Esteve-Lanao, et al., 2007; Weston, et al., 2000) were similar to corresponding values measured in African and Caucasian elite distance runners. Body fat percent and body mass in recreational runners were similar to those of elite distance runners (Kemmler, et al., 2006) and lower compared to those of international level middle- and long-distance runners (Maldonado, et al., 2002). In addition, RE at VT2track in competitive runners was comparable to earlier studies with highly trained middle- and long-distance runners (Fletcher, et al., 2009; Rabadan, et al., 2011). Therefore competitive and recreational runners in the present study were both at good level according to body composition and aerobic metabolism.

Competitive and recreational level athletes had similar RE at their VT1 and VT2 when running on track (Table 6). Speed at VT2track was significantly higher in competitive runners compared to recreational runners whereas only such tendency was found at VT1track. Maximal aerobic capacity was lower in recreational runners and therefore their individual threshold speeds were also lower than those in competitive runners'. In the present study, RE was measured at individual ventilatory thresholds and therefore it takes into account relative intensity of each athlete effort. Important finding is that athletes on different performance level, have similar RE at their individual thresholds. However, an earlier study (Billat, et al., 2003) has shown that high level runners who trained at higher speeds (at or above $\dot{V}O_{2max}$ speed) had greater $\dot{V}O_{2max}$ but also significantly lower RE than runners who trained at lower intensities. This finding was not confirmed in the present study where competitive athletes trained at higher running speeds and had higher $\dot{V}O_{2max}$ than recreational athletes. Possible explanation for these different findings could be the performance level of these athletes because Billat et al. (2003) had top level

Kenyan distance runners while in the present study athletes were only at national level.

In distance runners, an excess of adipose tissue usually requires a greater muscular effort to accelerate legs and, in theory, the energy expenditure at the same running velocity would be higher (Arrese & Ostariz, 2006). Earlier study indicated that runners with proportionally smaller amount of body mass concentrated in the extremities, particularly in the legs would perform less work moving their body segments during running, assuming that all other factors are similar (Myers & Steudel, 1985). Extraordinary RE may primarily be a characteristic of small people generally and specifically small people with thin lower legs. This works at a common sense level, as we know that adding weight, particularly at the end of a long lever (as in running shoes), is important to the energy cost of ambulation (Foster & Lucia, 2007). The aerobic demand is increased by 1% for every extra kilogram carried on the trunk, however, when the mass is carried in the shoes, aerobic demand increases by 10% for every additional kilogram (Myers & Steudel, 1985). It has been found that leg swing requires 20% of the net energy consumed in running (Modica & Kram, 2005). Therefore, it can be expected that thin and light lower legs lead to better RE. One important finding of this study was that competitive and recreational runners with similar height and body mass values were not different according to their body composition and relative leg mass patterning despite significant differences in performance level (see Table 7). Only lean body mass was significantly related to RE at VT2track in recreational runners, indicating that recreational runners with higher lean body mass have better RE. It was not the case in competitive athletes and possible reason might lay in greater body lean mass variance of the recreational runners. Competitive athletes body lean mass is achieved during long training years and are in very small range whereas recreational athletes have more space to increase or decrease lean body mass with their trainings.

Limitation of this study was the relatively low performance level in competitive runners and therefore differences between these two groups can be viewed only at the national level athletes. On the other hand strengths of this study are the DXA method for body composition evaluation, which is a very accurate method for body composition analyses and measured RE in field conditions. These two measurements have not been conducted simultaneously in previous studies with distance runners.

In conclusion, this study showed that there was no difference in RE at individual ventilatory thresholds between distance runners with different performance level when running on track while there was a difference in VT2track speed in different groups of distance runners. Moreover, running economy at competitive and recreational level runners cannot be explained by body composition and/or different leg mass ratios. It can be argued that running economy is rather influenced by specific training than body composition variables in national level distance runners.

## 6.4. Dissociation between running economy and running performance in national level Kenyan distance runners (III)

The factors responsible for the dominance of East African athletes in middle- and long-distance running have been the subject of considerable debate since their emergence in international competition in the 1960s (Foster & Lucia, 2007; Hamilton, 2000; Kong & de Heer, 2008; Larsen, 2003; Lucia, et al., 2006; Lucia, et al., 2008; Wilber & Pitsiladis, 2012). A prominent explanation has focused on the purported superior RE of the East African athletes and attributed to their unique anthropometric characteristics (Foster & Lucia, 2007; Lucia, et al., 2006; Lucia, et al., 2008; Wilber & Pitsiladis, 2012). This is the first study to systematically analyse the major putative anthropometric parameters that may explain RE and running performance in a relatively large and homogenous group of national level Kenyan distance runners. While in the present study, the tendon moment arm was associated with better RE and longer legs with better running performance, RE was not associated with running performance in these national level Kenyan distance runners. Therefore, on the basis of the present study and the related literature a superior RE *per se* could not account for the superior running performance of the East African runners compared to Caucasian runners. These results would suggest that in this homogenous group of distance runners, RE can be compensated for by other factors such as $\dot{V}O_{2max}$ to maintain high performance levels.

### 6.4.1. Running economy and anthropometric parameters

Results showed that the Achilles tendon moment arm was related to RE in this homogenous group of national level Kenyan distance runners and explained 30% of the variation in RE. This is somewhat in line with the results of earlier studies where the Achilles tendon moment arm explained 58−64% (Raichlen, et al., 2011; Scholz, et al., 2008) of the variation in RE in heterogeneous groups of non-elite distance runners. In the present study, significant relationships were also found between RE and BMI, mid-thigh and ankle circumference. However, these relationships were no longer significant after controlling each variable for covariation with the moment arm or controlling the moment arm for covariation with selected anthropometric variables (i.e. BMI, mid-thigh, ankle) (see Table 9 and 10). The observed correlation between Achilles tendon moment arm and RE supports the hypothesis that the storage and release of elastic strain energy in the Achilles tendon plays an important role in reducing the energy costs of running. The premise would be that runners with a short Achilles tendon moment arm would stretch their Achilles tendons to a greater degree than runners with a long Achilles tendon moment arm and therefore convert a higher percentage of kinetic energy into elastic energy, which is then returned leading to a lower energy cost of running (Raichlen, et al., 2011). However, Scholz et al. (2008) found that the moment arm was significantly related to RE even when controlled for other anthropometric variables that were related with RE (i.e. BMI, foot length). Collectively, these findings support the previously described idea that a shorter Achilles tendon moment arm is related with better RE. However, other parameters such as BMI, mid-thigh and ankle circumference, which are all related to RE in the same direction as the Achilles tendon moment arm, can also positively influence RE. Consequently, it can be argued that RE at the highest level of performance (e.g. elite East African runners) is determined not by one parameter but a complex interplay of numerous anthropometric characteristics. For instance, smaller leg circumferences can explain the lower energy cost of leg swing. Runners with proportionally smaller amount of body mass concentrated on the distal segments of the legs would perform less work moving their body segments during running, assuming that all other factors are similar (Myers & Steudel, 1985). This idea is supported by the finding that aerobic cost is increased by 1% for every extra kilogram carried on the trunk, however, when the mass is carried in the shoes, aerobic demand increases by 10% for every additional kilogram (Myers & Steudel, 1985). The widely reported idea that exceptionally good RE is a trait specific to small individuals with thin lower limbs (Foster & Lucia, 2007) is supported by the results of the present study where significant relationships between RE and BMI, mid-thigh and ankle circumference were found. Taken together, superior RE in this homogenous group of national level Kenyan distance runners would seem to be due to the interaction of efficient storage and release of elastic strain energy (i.e. shorter Achilles tendon moment arm), low BMI and low energy cost for leg swing (i.e. smaller mid-thigh and calf circumference) during running.

### 6.4.2. Performance and anthropometric parameters

Despite a number of studies describing body mass, body height and BMI (Billat, et al., 2001; Billat, et al., 2003; Fudge, et al., 2006; Lucia, et al., 2006; Marino, et al., 2004; Prommer, et al., 2010) in elite East African runners, there is a paucity of studies examining different leg length ratios and the relationship with running performance in competitive East African distance runners. Lower limb circumferences and lengths in the present study were similar to those reported earlier for elite East African runners (Kong & de Heer, 2008; Lucia, et al., 2006). Relationships between running performance and upper leg (thigh) length, total leg length and total leg length ratio to body height indicate that relatively longer legs are advantageous for running performance (see Figure 2). The precise underlying mechanism explaining this relationship is not clear (Lucia, et al., 2006). While leg length contributes to angular inertia and metabolic cost of moving the legs during running, there seems little consensus on whether leg length is an important factor in determining RE (Saunders, et al., 2004). Oscillating long legs increases the energy cost of running in proportion to the limb mass moment of inertia. Reduction in distal limb mass produces substantial metabolic savings during running. Furthermore, shorter ground contact time has been shown to be related to superior RE since there is less time for the braking force to decelerate forward motion of the body (Kong & de Heer, 2008, Nummela, et al., 2007; Santos-Concejero, et al., 2013). While increasing stride length is more efficient than increasing frequency by devoting less energy to leg acceleration, longer legs favour longer stride length and therefore would allow a better RE (Anderson, 1996; Rahmani, et al., 2004; Sleivert & Rowlands, 1996). However, this explanation is valid up to 90% of an individual maximum speed as, thereafter, the speed is mainly increased by increasing stride rate (Nummela, et al., 2007).

As seen above, several studies describing different anthropometric parameters in relation to RE automatically assume association between good economy and high performance (Kong & de Heer, 2008; Lucia, et al., 2006). However, the finding in the present study that running performance was not related to RE in this homogenous group of national level Kenyan runners is in line with an earlier studies with non-elite Caucasian runners (Foster, et al., 1977; Williams & Cavanagh, 1987). The implications of this now replicated finding are that the characteristics of an economical runner may not be related to any specific set of variables but instead to combined effect of many variables (Williams & Cavanagh, 1987). In addition, factors related to RE (i.e. BMI, Achilles tendon moment arm, mid-thigh and ankle circumference) are different to those that related with performance (e.g. upper leg length, total leg length and total leg length ratio to body height). Despite finding no relationship between RE and performance in the present study, there was an inverse relationship between $\dot{V}O_{2max}$ and RE, indicating that athletes with superior economy have a lower $\dot{V}O_{2max}$. This seemingly non-intuitive finding is also supported by the literature, where better RE was found to be associated with lower $\dot{V}O_{2max}$ in a heterogeneous group of recreational level male and female runners (Pate, et al., 1992) and an elite group of 10 km runners (Morgan & Daniels, 1994). Consequently, it can be argued that athletes with lower RE or possibly even cycling efficiency can compensate with a higher $\dot{V}O_{2max}$ (Lucia, et al., 2002; Morgan & Daniels, 1994). However, this hypothesis has been considered spurious due to a statistical artefact because of expressing both $\dot{V}O_{2max}$ and submaximal $\dot{V}O_2$ relative to body mass (Atkinson et al., 2003). Despite intense debate (Atkinson, et al., 2003; Lucia, et al., 2003; Morgan & Pate, 2004), there remains no consensus on the potential interactions between RE and $\dot{V}O_{2max}$, particularly as it relates to elite endurance performance. Furthermore, the finding that $\dot{V}O_{2max}$ was not related with running performance or any of the anthropometric parameters is in agreement with a previously published study (Conley & Krahenbuhl, 1980), also employing a homogenous group of elite male runners. In that study, while RE was related with 10 km race time, there was no significant relationship between $\dot{V}O_{2max}$ and running performance (Conley & Krahenbuhl, 1980). Finally, Noakes et al. (1990) reported that peak treadmill running velocity during a progressive treadmill test was a better predictor of running performance for marathon and ultramarathon runners compared with $VO_{2max}$. Present finding that $t_{max}$ on treadmill was not related to running performance did not confirm earlier findings (Noakes et al., 1990) for peak work rate reached during maximal exercise testing in predicting running performance. It can be explained by the fact that in present study more homogenous group of athletes from shorter distances than marathon was also included and because of the difference of protocols between present study and previous ones. While the high performance level of the Kenyan athletes in the present study can be explained by their generally good RE and high $\dot{V}O_{2max}$, neither of these two parameters is able to discriminate within the group in terms of distance running performance.

A limitation of the present study was evaluation of performance as on-going season IAAF performance scores and not conducting time trial close to $\dot{V}O_{2max}$ and RE test. Performance measured as described above, does not evaluate athletes performance at the same time point when $VO_{2max}$, RE and other anthropometrical variables are determined. However, IAAF performance score as a performance indicator in distance running have been used in previous studies (Legaz & Eston, 2005; Legaz, et al., 2007; Santos-Concejero, et al., 2013). It would be of interest to investigate RE in relation with performance and anthropometrical parameters also at higher running speeds, however in the present study, only available treadmill in Eldoret was used and increasing the speed higher than 17 $km \cdot h^{-1}$ on that treadmill, would have been dangerous for the athletes. One should be cautious to interpret associations with $\dot{V}O_{2max}$ since not all the athletes did reach a $VO_2$ plateau. As published earlier by Billat et al. (2003), elite level Kenyan distance runners who did not use $VO_{2max}$ intensity in their trainings were unable to reach a maximal $VO_2$ plateau probably due to lack of muscular force needed to sustain high speed.

$\dot{V}O_{2max}$ values in the present study are lower in comparison with earlier publications as the Kenyan athletes in the present study were measured at altitude (2 200 m a.s.l.): $\dot{V}O_{2max}$ values of Kenyan athletes measured at sea level are 6−16.6% higher than at altitude (altitude 2 200 m a.s.l.) (Saltin, et al., 1995; Tam, et al., 2012). The reported submaximal $\dot{V}O_2$ values at the speed of 16 $km \cdot h^{-1}$ in the present study were higher than previously published (Billat, et al., 2003; Lucia, et al., 2006; Tam, et al., 2012; Weston, et al., 2000), most likely due to the portable device used to measure $\dot{V}O_2$. For example, the MetaMax 3B used to measure $\dot{V}O_2$ in the present study has been shown to significantly overestimate $\dot{V}O_2$ by up to 10% when compared to the primary criterion Douglas bag method (Macfarlane & Wong, 2012; Vogler, et al., 2010) and secondary criterion Jaeger Oxycon Pro system (Macfarlane & Wong, 2012). Despite this overestimation, the MetaMax 3B has excellent reproducibility with a typical error of 2–3% for $\dot{V}O_2$, $\dot{V}CO_2$, $V_E$ (Vogler, et al., 2010). Furthermore, unpublished data from two studies, conducted with the same Metamax 3B device and using similar protocols demonstrated that national level Kenyan runners were 7.7% and European runners 8.8% more economical on the track than on the treadmill (1% inclination), with no significant difference between groups and therefore the systematic overestimation in $\dot{V}O_2$ reported here did not influence the outcome of the present study. In short, caution should be taken when comparing RE values from previous studies with the present one because different protocols and devices as well as methods have been used to calculate RE.

Unfortunately it was not possible to measure skinfolds or use the DXA method to assess the body composition of these national level Kenyan runners. It would also be of interest to measure upper leg, lower leg and total leg masses and to calculate different leg mass ratios as previously conducted in Caucasian runners (see Study I and II) and relate these measures with RE and performance in these distance runners.

In conclusion, while the Achilles tendon moment arm was associated with better RE and longer legs with better running performance, RE was not associated with running performance in national level Kenyan distance runners. The dissociation between RE and running performance in this homogenous group of distance runners would suggest that RE can be compensated for by other factors such as $\dot{V}O_{2max}$ and this finding is in line with the idea that RE is only one of many factors explaining elite running performance.

# 7. CONCLUSIONS

Based on the results of the current dissertation, the following conclusions were made:

1. Relatively lighter lower leg compared to upper leg is important factor for the prediction of the middle-distance but not the long-distance running performance in well-trained national level Estonian runners with relatively high $\dot{V}O_{2max}$ values.
2. There was no difference in RE at individual ventilatory thresholds between Estonian distance runners with different performance level when running on track.
3. RE of Estonian competitive and recreational level runners cannot be explained by body composition and/or different leg mass ratios and it can be argued that RE is rather influenced by specific training than body composition variables.
4. Good RE in homogenous group of national level Kenyan distance runners is the interaction of efficient storage and release of elastic strain energy (i.e. shorter Achilles moment arm), low BMI and low energy cost for leg swing (i.e. smaller mid-thigh and ankle circumference) during running.
5. RE is related with $\dot{V}O_{2max}$ but not with running performance in homogenous group of national level Kenyan distance runners, which would suggest that RE could be compensated for by other factors such as $\dot{V}O_{2max}$ to maintain high performance level.

# 8. PRACTICAL APPLICATIONS

1. It can be suggested that national level middle- and long-distance runners of even performance level and with no significant differences in anthropometric and/or body composition characteristics also present similar $\dot{V}O_{2max}$ values.

2. Middle-distance runners better $VT_2$time showed significant relationship with performance, indicating the importance of aerobic energy contribution to the middle-distance running performance.

3. RE of competitive and recreational level runners cannot be explained by the body composition. It can be argued that RE is rather influenced by specific training.

4. In homogeneous group of high level athletes it can be suggested that RE can be compensated for by $\dot{V}O_{2max}$ to produce high performance results.

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# SUMMARY IN ESTONIAN

## Pikamaajooksu ökonoomsuse ja võistlustulemuse antropomeetrilised ning füsioloogilised determinandid: Eesti harrastusjooksjatest rahvusliku tasemega Kenya jooksjateni

Ida-Aafrika, eriti Kenya, jooksjad on domineerinud kesk- ja pikamaajooksudes rohkem kui 40 aastat. Sporditeadlased on proovinud selle piirkonna jooksjate edu selgitada nii geneetika, keskkonna, kultuuri, sotsiaalmajandusliku, elustiili kui ka treeningu faktoritega. Varasemalt on näidatud, et Kenya jooksjate maksimaalse hapnikutarbimise väärtused ($\dot{V}O_{2max}$) ei erine oluliselt Euroopa jooksjate väärtustest ning seetõttu on pööratud üha suuremat tähelepanu jooksu ökonoomsuse (RE) uurimisele. Käesolevaks hetkeks puudub konsensus, kuidas on RE seotud võistlustulemusega, millised faktorid mõjutavad RE-d ja kas RE on kesk- ja pikamaajooksjatel erinev. RE on kompleksne faktor, millele pööratakse intensiivset tähelepanu kõrgeimal sportlikul tasemel ning seetõttu on vajalik parem arusaamine RE ja võistlustulemuse, keha koostise ning antropomeetriliste parameetrite vahelistest seostest.

Käesoleva töö peamine eesmärk oli uurida Eesti ning Kenya kesk- ja pikamaajooksjate RE-d ning võistlustulemust määravaid füsioloogilisi, antropomeetrilisi ja keha koostise näitajaid.

Vastavalt üldeesmärgile, püstitati järgmised ülesanded:

1. Võrrelda füsioloogilisi, antropomeetrilisi ja keha koostise parameetreid, mis on seotud võistlustulemusega Eesti rahvuslikul tasemel kesk- ja pikamaajooksjatel (Uuring I).
2. Võrrelda Eesti võistlus- ja harrastusjooksjate RE-d esimesel (VT1) ja teisel (VT2) ventilatsioonilävel sisehallis joostes (Uuring II).
3. Võrrelda Eesti võistlusjooksjate RE-ga seotud keha koostise näitajaid harrastusjooksjate näitajatega (Uuring II).
4. Selgitada millised antropomeetrilised parameetrid on seotud RE-ga ning võistlustulemusega rahvuslikul tasemel Kenya kesk- ja pikamaajooksjatel (Uuring III).
5. Selgitada RE ning võistlustulemuse vastastikust seost rahvuslikul tasemel Kenya kesk- ja pikamaajooksjatel (Uuring III).

Käesolev töö põhineb kolmel erineval uuringul. Uuring I ja II viidi läbi Eesti kesk- ja pikamaajooksjatega ning hinnati RE-d liikuval jooksurajal ning sisehallis joostes. Lisaks vaadati RE seost antropomeetriliste ja keha koostise parameetritega. Uuring III viidi läbi Kenyas sealsete kõrgel tasemel kesk- ja pikamaajooksjatega leidmaks võistlustulemuse ja RE seoseid antropomeetriliste näitajatega. Kenyas kasutati I ja II uuringuga samasid tehnilisi vahendeid ning metoodikaid.

Uuringus I osales 20 Eesti rahvuslikul tasemel keskmaajooksjat ning 20 pikamaajooksjat, kes sooritasid astmeliselt tõusvate koormustega testi koos hapnikutarbimise ja RE määramisega liikuval jooksurajal. Lisaks mõõdeti 29 antropomeetrilist parameetrit ja keha koostis DXA meetodil ning arvutati 4 erinevat antropomeetrilist ja 4 erinevat keha segmentide masside suhet.

Uuringus II osales 28 Eesti võistlusspordi tasemel jooksjat ning 17 harrastusjooksjat, kes sooritasid astmeliselt tõusvate koormustega testi liikuval jooksurajal ning vähemalt 48 tundi hiljem 2 × 2 000 m jooksutesti (vastavalt VT1 ja VT2 intensiivsustele) sisehallis koos hapnikutarbimise ning RE määramisega. Lisaks mõõdeti 29 antropomeetrilist parameetrit ja keha koostis DXA meetodil ning arvutati 4 erinevat keha segmentide masside suhet.

Uuringus III osales 32 kõrgel tasemel Kenya jooksjat, kes sooritasid astmeliselt tõusvate koormustega testi liikuval jooksurajal. Lisaks mõõdeti Achilleuse jõuõlg, 11 antropomeetrilist parameetrit ning arvutati 4 erinevat antropomeetrilist suhet.

Vastavalt töö tulemustele tehti järgmised järeldused:

1. Suhteliselt väiksem sääre mass võrreldes reie massiga on oluline parameeter Eesti tasemel keskmaa-, kuid mitte pikamaajooksjate võistlustulemuse prognoosimisel.
2. Eesti harrastusjooksjate ja võistlustasemel jooksjate gruppide vahel puudub ökonoomsuses erinevus, mõõdetuna individuaalsete ventilatsiooni lävede (VT1 ja VT2) intensiivsustel.
3. Erinevusi Eesti harrastus- ja võistlusjooksjate RE-s ei saa selgitada keha koostise ja/või erinevate jalgade masside suhetega.
4. Kõrgel tasemel RE rahvusliku tasemega Kenya jooksjatel on kompleks efektiivsest elastsusenergia salvestamisest ja vabastamisest (lühem Achilleuse kõõluse jõuõlg), madalast kehamassi indeksist ning jooksmisel jalgade liigutamise väikesest energiakulust (väiksem reie ning hüppeliigese ümbermõõt).
5. Rahvuslikul tasemel Kenya jooksjate ökonoomsus ei ole seotud võistlustulemusega, kuid on seotud maksimaalse hapnikutarbimise näitajatega, mis viitab, et RE-d on võimalik kompenseerida teiste faktoritega, nagu näiteks maksimaalse hapnikutarbimise arvelt, saavutamaks kõrgeid võistlustulemusi.

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