Article published online: 2020-10-14

Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat

Authors

Marietta Sengeis[1, 2], Wolfram Müller[1], Paul Störchle[1], Alfred Fürhapter-Rieger[1]

Affiliations

1 Institute of Biophysics, Medical University of Graz, Graz,

2 Sport Science, Anthropometry, Leistungssport Austria, High Performance Center, Brunn am Gebirge

Key words

ultrasound imaging, subcutaneous fat, body mass index, marathon, anthropometry, sexual dimorphism

accepted 09.09.2020

published online 14.10.2020

Bibliography

Int J Sports Med 2021; 42: 323–335

DOI 10.1055/a-1268-8339

ISSN 0172-4622

Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence

Dr. Wolfram Müller

Institute of Biophysics, Medical University of Graz, Harrachgasse 21/4

8010 Graz

Austria

Tel.: +43 316 380 3913,

wolfram.mueller@medunigraz.at,

wolfram.mueller@rotosport.at

ABSTRACT

Body fat values obtained with various measurement methods deviate substantially in many cases. The standardised brightness-mode ultrasound method was used in 32 Kenyan elite long-distance runners to measure subcutaneous adipose tissue thicknesses at an accuracy and reliability level not reached by any other method. Subcutaneous adipose tissue forms the dominating part of body fat. Additionally, body mass (m), height (h), sitting height (s), leg length, and the mass index $MI_1 = 0.53m/(hs)$ were determined. MI_1 considers leg length, which the body mass index ignores. MI_1 values of all participants were higher than their body mass indices. Both indices for relative body weight were within narrow ranges, although thickness sums of subcutaneous adipose tissue deviated strongly (women: 20–82 mm; men: 3–36 mm). Men had 2.1 times more embedded fasciae in the subcutaneous adipose tissue. In the subgroup with personal best times below world record time plus 10 %, no correlation between performance and body mass index was found, and there was also no correlation with sums of subcutaneous adipose tissue thicknesses. Within the data ranges found here, extremely low relative body weight or low body fat were no criteria for the level of performance, therefore, pressure towards too low values may be disadvantageous.

Introduction

Human body composition is a predominant performance factor in many sports [1, 2]. In weight-sensitive sports [2], many athletes use hazardous methods to reduce their body mass rapidly or to keep it at an extremely low level, which can cause severe health problems resulting from the associated body composition disturbances [2–5]. The International Olympic Committee (IOC) is concerned about athletes who use such unhealthy strategies and, therefore, set up in 2012 a working group on Body Composition, Health and Performance in Sports. This working group published a position statement on how to minimise the health risks to athletes who compete in weight sensitive sports [6]. Currently, there are still no generally recommended lower limits of body mass, or fat values for female and male elite athletes competing in weight sensitive sports; one reason for this is that body fat values obtained with various measurement methods deviate substantially from each other.

Measurement of the athletes' body composition is not a simple task [2]: widely used field methods (e. g., skinfolds, bio-impedance analysis (BIA), anthropometric measures and indices) and laboratory methods (e. g., dual energy X-ray (DXA), MRI, CT, densitometry) for body composition assessments do not work on the fine scale needed for performance and health analyses of top level athletes, particularly if their physique is not in line with morphological norms of the 'reference person' used in the underlying assumptions of these methods [2, 7, 8]. Using DXA and densitometry, for example, negative amounts of fat resulted from measurements in groups of lean athletes; such impossible results demonstrate that the assumptions underlying these methods are not valid for use with athletes [9, 10].

Ultrasound (US) was found to be a promising method because of the high image resolution obtainable with high frequency brightness-mode (B-mode) imaging [2, 11–13]. The image resolution and thus the accuracy of US measurements of subcutaneous adipose tissue (SAT) thickness is approximately 0.1–0.2 mm when using probe frequencies between 9 and 18 MHz, provided that the appropriate sound speed of the tissue under study is used (which may deviate substantially from 1540 $m \cdot s^{-1}$ used in conventional diagnostic US systems) [11, 12, 14].

In order to optimise reliability, this recently developed method for measuring SAT, has been standardised: SAT compression is avoided by a thick layer of US gel, eight sites are used to represent trunk, arms, and legs, marking of sites and US measurements are done in defined body positions, and all marking distances are percentages of stature [14]. Inter-observer reliability (95 % limit of agreement, LOA) was found to be ± 1.1 mm [14] when athletes with sums of SAT thicknesses D_I (the index I indicates that embedded fasciae are included in the thickness measurement) up to 50 mm were studied [14], and ± 1.2 mm in a group of athletes with D_I values up to 70 mm [15]. Most recently, similar reliability results were found within the framework of an international multi-centre study when three experienced measurers of each of two participating centres measured each of the 16 elite athletes (of various sports) of their centres. However, LOA values were larger when novice measurers at each of the three participating 'novice centres' performed the measurements, indicating that training of measurers is important. The 95 % LOA in D_I of less than 1.5 mm enables tracking body fat changes on an accuracy level of 0.2 kg [16]; this is almost an order of magnitude below the daily weight changes. The method can be applied in all groups of body fatness reaching from extremely lean athletes and anorectic patients to overweight and obesity groups [15, 17]. The standardised US method used here [14–16] enables studies of SAT on a fine scale that is not reached by any other method. SAT is the major part of total (anatomically detectable) body fat [18–20]. The accuracy limits of this method are determined by biological reasons: furrowed borders of the tissue (the micro-elevations along the tissue borders are larger than the image resolution), but not by technical limitations of this measurement approach [2, 11, 12, 14–16].

There is no generally accepted model that analyses the role of body fat in long-distance running from all perspectives of relevance: biomechanics, bioenergetics, and the health point of view. In long distance running, the athlete's centre of gravity is moved upwards and downwards, and several parts of the body are accelerated and decelerated at every step. The energy needed for these dynamic actions are linearly related to the involved body masses, and therefore - from this biomechanics point of view - increased (passive) body masses limit performance. On the other hand, 'wobbling masses are a means to reduce high impacts by suspending the muscles' visco-elasticity to the skeleton' [21]. From the bioenergetics points of view, it has to be considered that: 'Blood glucose and liver and muscle glycogen stores are inadequate over protracted periods to both fuel exercise and maintain blood glucose level. Therefore, the ability to use fats as fuels is essential' [22]. Extremely low body weight and body fat can lead to disastrous performance set-backs and to severe medical problems [3, 5, 6, 23]. In this study, we investigated body composition and relative body mass ('ponderosity') in world class Kenyan long-distance runners. Relative body weight was measured by using the mass index ($MI_1 = 0.53\ m/(hs)$), which considers the individual's body proportions that the body mass index ($BMI = m/h^2$) ignores [24–27]. However, both indices can only be used to characterise relative body mass, but are not useful to assess body composition in athletes [2].

Preliminary normative data of SAT among competitive athletes have recently been published [28]. Results described here can be compared to the first studies using this US method in elite judokas [29], in competitive junior rowers [30], and in a mixed group of 76 elite athletes of various sports investigated in five research centres [16].

The aims of the present study were to address the following questions:

- How to the ranges of SAT thickness sums (D_I and D_E) compare in female and male groups of athletes?
- What are the ranges of relative body weight in terms of the improved measure for relative body weight MI_1, and how do BMI and MI_1 compare in this group of Kenyan athletes?
- Are BMI and MI_1 correlated with performance?
- Is body fat, represented by SAT thickness sums D_I and D_E, correlated with performance?
- Are there differences between females and males in the amounts of fibrous structures (fasciae) embedded in the SAT?
- Does the fat patterning, represented by the eight standardised sites on trunk, arms, and legs, characterise female and male athletes?

Materials and Methods

Participants and locations where the study took place

The study includes 32 elite female and male Kenyan long-distance runners competing in international long-distance running events (10 000 m, half marathon, marathon, and mountain running). The group of Kenyan athletes included 7 female and 25 male long-distance runners. The four mountain runners (number 3, 9, 19, 22 in ▶ **Table 2b**) are not included in the performance analyses. The study took place in Kenya, at the Mount Longonot Sports & Recreation Camp (April 8–14, 2017; elevation of 2400 m above sea level) and in Austria, at Hochrindl/Turrach (August 31–September 1, 2017; 1600 m above sea level). All athletes gave their written informed consent prior to the measurements. The study was conducted in accordance with the Ethical Standards in Sport and Exercise Science Research: 2020 Update [31] and approved by the ethics committee of the Medical University of Graz (20–295 ex08/09).

Observer

All measurements were performed by the same experienced observer. The observer had been trained according to the International Association of Sciences in Medicine and Sports (IASMS ; www.iasms.org) for SAT thickness measurements using the standardised US imaging technique. All anthropometric measurements were carried out according to the International Society for the Advancement of Kinanthropometry (ISAK) [32] by the same ISAK Level 2 certified observer.

Anthropometry and US marking

Anthropometric measurements were performed in accordance with the ISAK protocol [32] and included: body mass (*m*), stature (*h*), sitting height (*s*), leg length (*l*), waist girth (*w*), gluteal (hip) girth (*g*), biceps girth with arm flexed (90°) and tensed (*b*), and thigh girth (*t*) at the site front thigh (FT). US measurements for SAT detection were performed in accordance with the standardised protocol [14, 15]. Before US images were captured, all athletes were marked on the right side of the body in defined standing or sitting positions, or with the arm or foot supported. All marking distances were percentages of the individual's stature. All US images were captured in defined lying positions: upper abdomen (UA), lower abdomen (LA), brachioradialis (BR) and front thigh (FT) in supine, erector spinae (ES) and distal triceps (DT) in prone, and lateral thigh (LT) and medial calf (MC) in rotated position. The standardised eight measurement sites are [14, 15]: UA, LA, FT, LT, MC, ES, DT, and BR. For calculating the relative body weight, the BMI = m/h^2 and the improved measure for relative body weight MI_1 ($MI_1 = 0.53\,m/(hs)$) were used [2, 25, 26]. The MI_1 has been defined such that the World Health Organisation (WHO) cut-off points for underweight and overweight, and also the relative weight criterion (17.5 kgm^{-2}, [33]) for diagnosing of anorexia nervosa (as one of the diagnostic criteria) can remain unaltered.

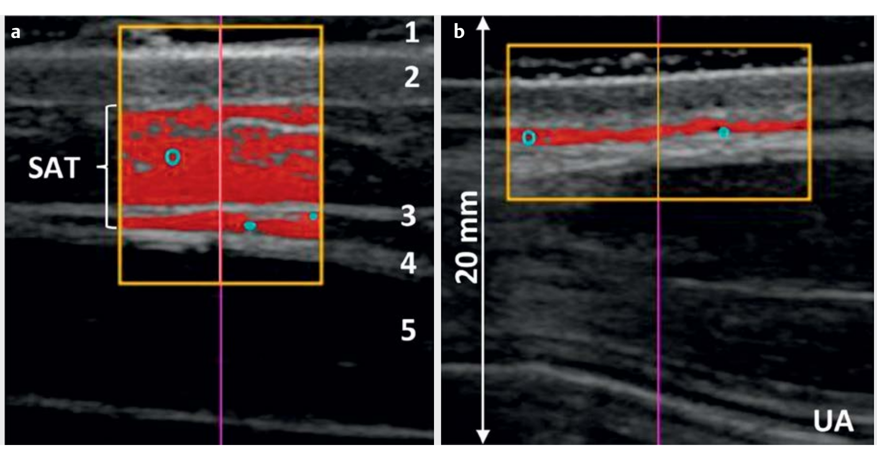
B-Mode US imaging and SAT thickness evaluation

For US imaging, a portable B-Mode ultrasound device (Phillips CX50, L12–3) was used. Tissue compression was avoided by using a thick layer of US gel (approximately 3–5 mm) [12, 14]. The black bands on top of the US images (▶ **Fig. 1**) correspond to the gel layer between the probe and the skin. The US probe was placed perpendicularly to the skin surface and directly above the marked site. US images of the standardised site UA are shown for two athletes in ▶ **Fig.1a** and **b**. For SAT thickness evaluation, the inter-active software *NISOS - BCA - F (version 3.3*; *Rotosport, Austria; rotosport.at*) was used [11, 14]. A sound speed of 1450 ms^{-1} was set for thickness determination in adipose tissue [14–16, 20]. The algorithm measures typically between 50 and 200 thicknesses in each US image, depending on the width of the chosen region of interest (ROI). The automatic measurements are done in close vicinity of the marked site (within the chosen ROI; compare to ▶ **Fig. 1**). Typically, the raw of measurements covers a few millimetres on both sides of the image centre. One of the criteria for choosing the standardised eight sites (out of a large number of tested sites) was to select sites that showed low variation of SAT thickness in the surrounding of the marked point [12, 14, 15]. Because ROIs are usually chosen around the image centre (corresponding to the middle beam of the US ray series), thickness differences resulting from different ROI widths are minimal and usually an order of magnitude smaller than the obtainable reliability that results from the US imaging deviations. Details on the choice of sites and on reliability and accuracy can be found in previous publications [11, 14].

The mean thickness at a given site is termed *d*; the thicknesses at the eight sites represent the fat patterning of the athlete. The sums of these eight sites (D_I and D_E) are representatives of the athlete's SAT amount with fibrous structures (fasciae) included (Index I) or excluded (Index E). Detailed information on the measurement method can be found in preceding publications [12, 14, 15].

Statistical methods

SPSS (v25.0) software (IBM® SPSS® Statistics) was used. Descriptive statistics include means ± standard deviations (SD). Data were tested for normality of distribution using the Shapiro-Wilk test. Pearson's (r) or Spearman's (r_s) correlation coefficient were used to assess relationships between BMI and MI_1 with D_I, and D_E, respectively. For normally distributed data, Pearson's correlation was used, not normally distributed data was investigated with Spearman's rank correlation. The t-test was used to compare BMI with MI_1, and for analysing sexual dimorphism of the differences MI_1-BMI. The Mann-Whitney U test was applied to compare possi-



▶ **Fig. 1** Subcutaneous adipose tissue (SAT) of two male long-distance runners with similar body mass index (BMI), but large differences in SAT thickness sums (D_I). **a** Site upper abdomen (UA) of athlete number 2 (of ▶ **Table 2S** in the Supplementary Material, SM) (PB: 10k: 00:28:59, HM: 01:02:45, BMI = 19.0 kgm^{-2}, mass index MI_1 = 19.4 kgm^{-2}, sum of the eight standardised sites D_I = 20.2 mm). The index I indicates that embedded fibrous structures are included in the thickness measurements. Numbers indicate: 1: gel, 2: skin, 3: embedded fibrous structure, 4: muscle fascia, 5: muscle. The yellow frame represents the chosen region of interest (ROI). Numbers of thickness measurements within the ROI: the mean of these 141 thicknesses represents the thickness d_I = 5.4 mm at this site. **b** UA of athlete number 5 (of ▶ **Table 2S** in the SM) (PB: M: 02:15:18, BMI = 18.7 kgm^{-2}, mass index MI_1 = 19.8 kgm^{-2}, sum of the eight standardised sites D_I = 6.0 mm). Numbers of thickness measurements: 209, d_I = 0.53 mm at this site.

▶ **Table 1** Descriptive statistics of the Kenyan elite female (K_f) and male (K_m) long-distance runners.

		K_f (N = 7)			K_m (N = 25)		
Variable	**Unit**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**
age	[years]	24.1 * (5.6)	19.0	34.0	27.2 * (3.3)	20.0	33.0
m	[kg]	50.5 * (2.6)	45.8	53.1	54.0 * (4.3)	43.5	61.8
h	[m]	1.647 * (0.065)	1.566	1.780	1.680 * (0.058)	1.547	1.792
s	[m]	0.835 (0.037)	0.810	0.915	0.847 (0.026)	0.810	0.893
l	[m]	0.954 * (0.040)	0.880	1.010	0.963 * (0.044)	0.865	1.042
BMI	[kgm^{-2}]	18.6 * (0.9)	16.8	19.5	19.1 * (1.2)	16.1	20.7
MI1	[kgm^{-2}]	19.5 * (1.1)	17.3	20.7	20.1 * (1.2)	17.6	22.0
w	[m]	0.633 * (0.018)	0.612	0.663	0.669 * (0.028)	0.610	0.732
g	[m]	0.863 * (0.027)	0.828	0.890	0.835 * (0.030)	0.775	0.895
b	[m]	0.238 * (0.009)	0.229	0.251	0.259 * (0.014)	0.220	0.282
t	[m]	0.436 * (0.017)	0.408	0.457	0.441 * (0.023)	0.390	0.474
L = *l/h*	[1]	0.579 * (0.011)	0.56	0.59	0.573 * (0.011)	0.55	0.60
C = *s/h*	[1]	0.506 (0.008)	0.50	0.52	0.505 (0.011)	0.49	0.52
W = *w/h*	[1]	0.385 (0.017)	0.35	0.40	0.398 * (0.020)	0.35	0.44
10 k	[hh:mm:ss]	00:33:45 (0:01:12)	00:32:17	00:35:22	00:29:23 (0:00:42)	00:28:19	00:30:43
HM	[hh:mm:ss]	01:14:16 (0:02:54)	01:11:20	01:19:58	01:04:08 (0:01:32)	01:02:32	01:07:07
M	[hh:mm:ss]				02:13:59 (0:01:41)	02:12:00	02:16:51

Normal distribution (Shapiro-Wilk test) is marked with (*). Abbreviations: body height (*h*), body mass (*m*), sitting height (*s*), leg length (*l*), leg-to-height ratio (L = *l/h*), body mass index (BMI = m/h²), mass index (MI_1 = 0.53.m/hs)), Cormic index (C = *s/h*), waist girth (*w*), *g*luteal (hip) girth (*g*), biceps girth with arm flexed (90°) and tensed (*b*), thigh girth at the site front thigh (*t*), waist-to-*h*eight ratio (W = *w/h*). Means (± SD) of personal best times of the latest two years (2016–2018) were included: 10 kilometer (10 k) K_f = 6, K_m = 12, half marathon (HM) K_f = 7, K_m = 12, marathon (M) K_m = 6.

ble differences in SAT and in embedded fibrous structures in female and male athletes. The paired t-test or Wilcoxon test was applied for comparisons of E1 (measurement series in Kenya) and E2 (a second series in Austria, 18 weeks later) in a sub-group of nine Kenyan runners. Pearson's and Spearman's correlation (according to distribution) were used to analyse relationships between running performance and D_I, and between running performance and MI_1.

Results

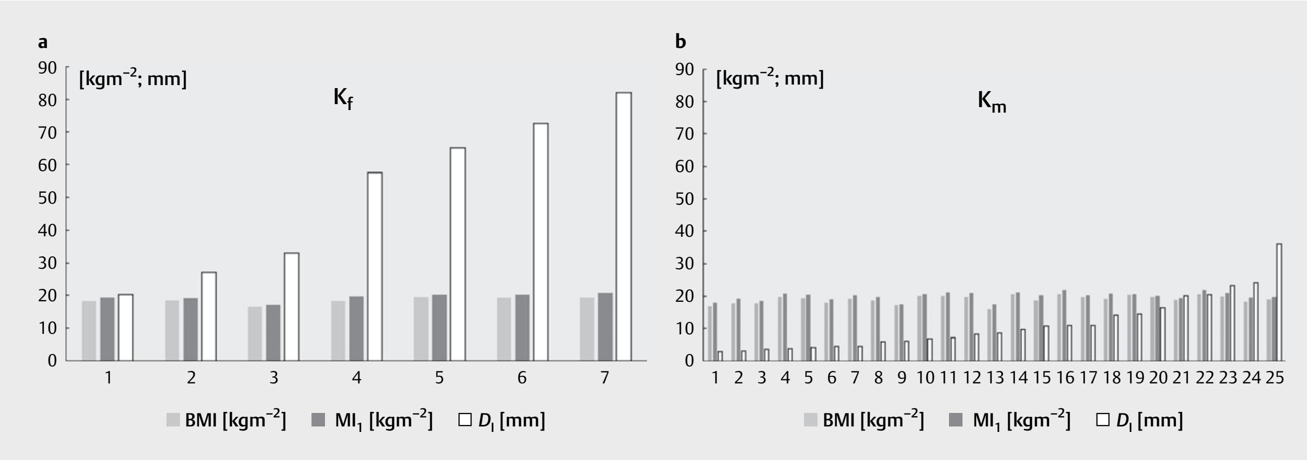
Mean values of age, body height, body mass and selected body dimensions (lengths, circumferences, and indices) are shown in ▶ **Table 1**.

▶ **Figs. 1a** and **b** show two US images of two exemplarily chosen male Kenyan long-distance runners. Athletes in images A and B (number 2 and 5 of ▶ **Table 2S** in the Supplementary Material, SM) had similar BMIs (19.0 kgm^{-2}, and 18.7 kgm^{-2}), but enormous differences (240 %) in the SAT sums of the eight sites (A: D_I = 20.2 mm; B: D_I = 6.0 mm). The ▶ **Figs 1a** and **b** show the SAT thicknesses (d_I) at the site UA (A: $d_{I,UA}$ = 5.4 mm; B: $d_{I,UA}$ = 0.53 mm). Personal best times were: A: 10 km: 00:28:59; half marathon: 01:02:45, and B: marathon: 02:15:18; for comparison to other participants see ▶ **Table 2S** in the SM. In the UA image on the left side, the SAT is coloured in red, and the structures of relevance for the semi-automatic contour detection and image evaluation are indicated. All images were evaluated with the semi-automatic SAT contour detection algorithm, which starts out from the blue circles set by the observer within the SAT compartments. The yellow frame represents the chosen region of interest (ROI). The numbers of SAT thickness (*d*) measurements in these two US images (1A and 1B) were 141 and 209, respectively, which resulted in robust mean and median thickness values.

▶ **Figs 2a** and **b** show the relative body weights of female and male participants, respectively, represented by both the body mass index (BMI) and the mass index (MI_1); the latter takes the individual's sitting height into account (and thus, implicitly, also leg length). The columns are ordered according to increasing SAT thickness sums (D_I). All athletes (N = 32) had higher MI_1 than BMI values, indicating their longer legs when compared to groups of White Caucasians [34, 35]. There was no significant correlation between D_I and BMI (r = 0.643, p = 0.119) or MI_1 (r = 0.728, p = 0.063) in the female long-distance runners (K_f). In the male group (K_m), there was a moderate correlation between D_I and BMI (r_s = 0.427, p = 0.033), but not between D_I and the improved measure for relative body weight MI_1 (r_s = 0.340, p = 0.096).

In ▶ **Figs 3a** and **b**, the 'underweight' border line defined by the WHO [36] (BMI = 18.5 kgm^{-2}) is marked in red. When using the BMI for relative body weight, seven male and three female athletes were underweight, four of them were even below 17.5 kgm^{-2}. When using the MI_1 instead of the BMI (▶ **Fig. 3b**), only three male and one female athlete were 'underweight', and only one female athlete was below 17.5 kgm^{-2}. The BMI and the improved measure for relative body weight MI_1 differed significantly in both the female (t (6) = -6.494, p = 0.001) and the male group (t (24) = –11.339, p < 0.001) because of athletes' long leg lengths (associated with small sitting heights *s*).

The differences MI_1 - BMI are shown in ▶ **Fig. 3c**; they ranged from 0.4 kgm^{-2} to 1.3 kgm^{-2} in females (bright grey columns) and



▶ **Fig. 2** Relative body mass (body mass index BMI, mass index MI_1), and subcutaneous adipose tissue (SAT) thickness sums (D_I): **a** Group of female athletes (K_f). The columns represent BMI, the MI_1, and the SAT thickness sums (D_I) of the eight standardised measurement sites. The index I refers to thickness sums including embedded fibrous structures. Abbreviations: (*m*) body mass, (*h*) stature, (*s*) sitting height. The values of the female Kenyan runners (K_f) are ordered according to their D_I. There was no significant correlation between D_I and BMI (r = 0.643, p = 0.119) or MI_1 (r = 0.728, p = 0.063). **b** as in A, but for male Kenyan runners (K_m). There was a moderate correlation between D_I and BMI (r_s = 0.427, p = 0.033), but not between D_I and MI_1 (r_s = 0.340, p = 0.096).

from 0.3 to 1.7 kgm^{-2} in males (dark grey columns). All MI_1 values were higher than the BMI values. For the differences MI_1 – BMI, there was no significant difference (t (30) = 0.622, p = 0.539) between females ($K_{f,MEAN}$: 0.9 ± 0.3 kgm^{-2}) and males ($K_{m,MEAN}$: 1.0 ± 0.4 kgm^{-2}).

▶ **Figs. 4a** and **b** show the subcutaneous fat patterning (thicknesses *d* at the eight individual measurement sites); all eight sites differed significantly between the groups K_f and K_m. The highest ratio of the median SAT thicknesses with fibrous structures included (d_I) was measured at the site lateral thigh (LT: 15.0/0.8 = 18.8), the lowest ratio at the site distal triceps (DT: 5.4/1.7 = 3.2). The ratios of all sites were: UA: 6.6/1.0 = 6.6, LA: 9.0/1.8 = 5.0, FT: 5.3/0.9 = 5.9, LT: 15.0/0.8 = 18.8, MC: 4.5/0.6 = 7.5, ES: 4.5/0.9 = 5.0, DT: 5.4/1.7 = 3.2, and BR: 1.9/0.2 = 9.5. When fibrous structures embedded in the SAT were excluded in the thickness measurements (d_E), the ratios were: UA: 5.8/0.9 = 6.4, LA: 6.8/1.2 = 5.7, FT: 4.6/0.7 = 6.6, LT: 13.8/0.3 = 46.0, MC: 4.4/0.5 = 8.8, ES: 2.7/0.7 = 3.9, DT: 5.0/0.8 = 6.3, and BR: 1.3/0.2 = 6.5.

▶ **Fig. 4c** shows the SAT thickness sums including (D_I) or excluding embedded fibrous structures (D_E), and additionally, the percentages of embedded fibrous structures 100 · F/D_I. Males showed significantly lower D_I (Z = –3.715, p < 0.01) and D_E (Z = –3.715, p < 0.01) values. The percentages (P) of fibrous structures (F) were significantly lower in females (t (30) = 3.846, p = 0.001), which further increases the body fat content in the female group.

In ▶ **Table 2**, two measurement series E1 (in Kenya) and a second series E2 (in Austria, 18 weeks later) performed with a subgroup of nine male athletes are compared. There were no statistically significant differences (p > 0.05) between E1 and E2 concerning the variables BMI, MI_1, D_I, and D_E. At the individual eight sites, the SAT thicknesses (d_I) also did not differ significantly.

For both groups K_f (females) and K_m (males), relationships between running performance (ΔWR: percentage of time above the world record) and SAT thickness sums (D_I) are shown in ▶ **Figs. 5a** and **b**. In the male group (N = 19; performance level better than WR plus 15 %), higher body fat (represented by SAT thickness sums D_I and D_E) was not associated with lower performance (i. e., a higher ΔWR); in the opposite, there was a (weak) negative correlation between D_I and ΔWR (r_s = –0.390, p = 0.033). In the male sub-group with a performance level better than WR plus 10 % (N = 12; D_I was 13.4 ± 9.4 mm), no correlation (r_s = 0.019, p = 0.950) was found. The performance of the best females (performance level close to WR plus 10 %, N = 3) also did not show a dependency of ΔWR on D_I, however, for the whole group of females (N = 7), there was a significant positive correlation (r = 0.782, p = 0.002).

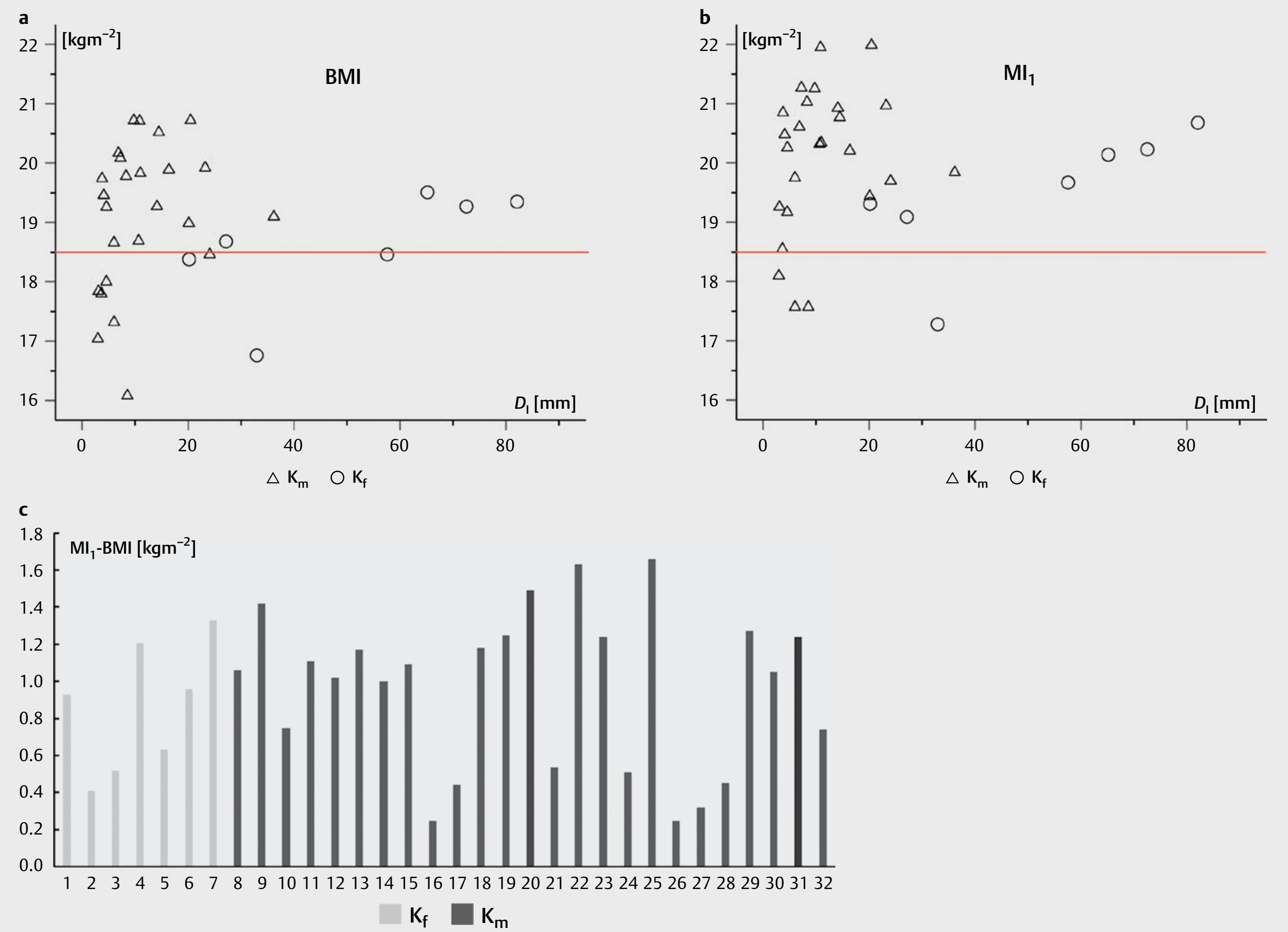
In the male group (N = 19), there was no correlation between running performance and relative body weight in terms of MI_1 (r_s = –0.152, p = 0.424). In the female group (N = 7), a significant positive correlation was found (r_s = 0.835, p < 0.001). Using the BMI instead of the MI_1 resulted in analogous findings. The results with females should be interpreted with caution because of the low number of participants and the higher heterogeneity in performance (see ▶ **Figs. 5a** and **c**).

Discussion

Competitive performance and body fat

In the female group, five PB running times (71 %) were below the WR time plus 15 %, and three were close to WR time plus 10 %. The PB times of nineteen male athletes (i. e., 95 % of male participants) were better than WR time plus 15 %, and 12 (50 %) were better than WR time plus 10 %.

In the female group, there was a significant positive correlation between the deviations of their PB times from the WR (ΔWR) and their SAT thickness sums D_I (r = 0.78, p = 0.002), but this does not hold true for the three female athletes with PB times close to 10 % above the WR: the D_I-values of the female runners of this higher

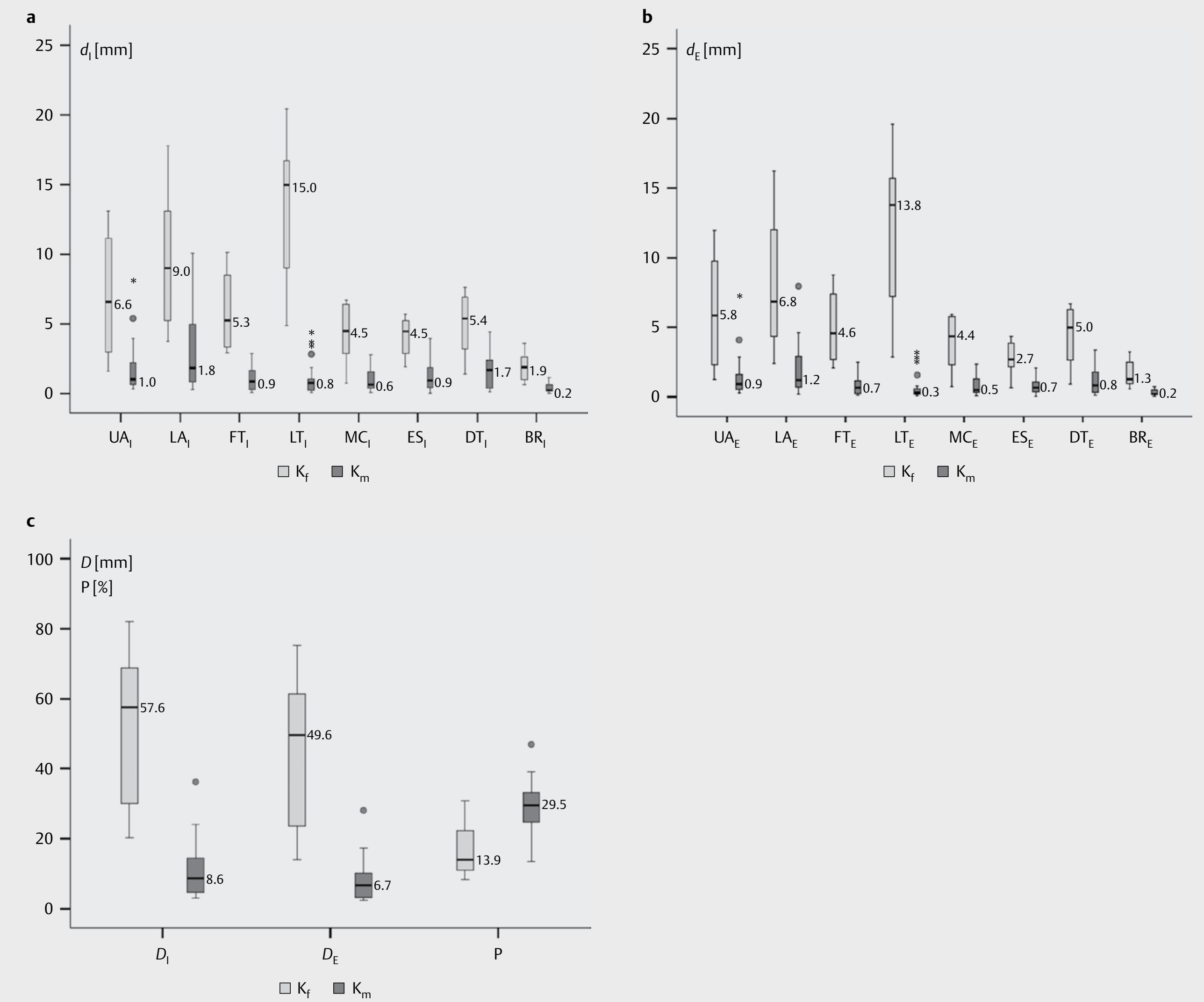


▶ **Fig. 3** Underweight in terms of body mass index (BMI) and mass index (MI_1): **a** The 'underweight' cut-off line (BMI = 18.5 kgm^{-2}; according to the WHO [36]) is marked in red. In both groups (females: K_f; males: K_m), neither BMI nor MI_1 differed significantly (BMI: Z = –1.208, p = 0.242; MI_1: Z = –1.527, p = 0.135), but there was a highly significant difference between subcutaneous adipose tissue (SAT) thickness sums (D_l) between K_f and K_m (Z = –3.715, p < 0.001). The BMI and the MI_1 differed significantly in K_f (t (6) = –6.494, p = 0.001) and in K_m (t (24) = –11.339, p < 0.001). Abbreviations: D_l sum of the eight standardised sites with fibrous structures included. **b** as in A, but instead of the BMI the MI_1 is used. When using the MI_1, only four athletes were below the cut-off line for 'underweight' [36]. **c** Differences between MI_1 and BMI: All MI_1 values were higher than the according BMI values. Differences in the group (K_f) ranged from 0.4 to 1.3 kgm^{-2}, and in the male group (K_m) from 0.3 to 1.7 kgm^{-2}. MI_1 and BMI differed significantly (t (30) = -13.073, p < 0.01).

performance class were all between 20 and 35 mm. According to preliminary normative data [28], two of them were in the category 'low' body fat, and one was in the category 'extremely low'. The median value of the whole female group was 58 mm (ranging from 20.2 to 82.1 mm), which is close to median values found previously in other sports: in a group of 16 elite female adult judokas, the median was 65 mm (ranging from 45 to 88 mm) [29], and the eight female athletes of the German National rowing team (U 19) had a median of 70 mm (48 to 79 mm) [30]. Compared to the male long-distance runners, the females' D_l-median was about six times higher, indicating that adipose tissue, which has important endocrine functions [37], plays a substantial role in females.

In the male group, there was no correlation (r = 0.02, p = 0.950) when using the data of those 12 athletes whose running times were below WR plus 10 %; although their performance levels were close to each other, there was a surprisingly large range of SAT thickness sums D_l (from 3 to 36 mm). When studying the whole group of 20 male runners, there was even a weak negative correlation between the deviations of their PB times (ΔWR) from the WR and their SAT thickness sums D_l (r_s = –0.39, p = 0.033).

Seen from a health perspective: "There are no generally accepted optimum values for body weight or percentage of fat mass in different sports…" [6]. Data of this and of previous studies [16, 29, 30] clearly indicate that the search for optimum body fat values and cut-off criteria for raising the alarm has to distinguish between sexes and to consider that such limits may largely depend on genetic differences of the sexes and between individuals [2]. The question how to minimise the health risks to athletes who compete in weight-sensitive sports has been discussed in a consensus statement of the IOC Working Group on Body Composition, Health and Performance [6]. Features of long-distance runners from Kenya have previously been analysed by Hamilton [38]. However, research



▸ **Fig. 4** Subcutaneous adipose tissue (SAT) patterning, and SAT thickness sums D_I and D_E. **a** SAT thickness patterning (d_I) at the eight standardised body sites including embedded fibrous structures (index I) in female (K_f) and in male (K_m) long-distance runners. All eight standardised body sites differed significantly between K_f and K_m. (UA) upper abdomen (Z = -3.123, p = 0.002), (LA) lower abdomen (Z = –3.259, p = 0.001), (FT) front thigh (Z = –3.989, p < 0.01), (LT) lateral thigh (Z = –3.989, p < 0.01), (MC) medial calf (Z = –3.350, p = 0.001), (ES) erector spinae (Z = –3.487, p < 0.01), (DT) distal triceps (Z = –3.123, p = 0.002), and (BR) brachioradialis (Z = –3.624, p < 0.01). **b** as in A, but the embedded fibrous structures are excluded in the SAT measurements (d_E). All eight body sites showed significant differences between K_f and K_m. UA (Z = –3.259, p = 0.001), LA (Z = –3.305, p = 0.001), FT (Z = –3.806, p < 0.01), LT (Z = –3.943, p < 0.01), MC (Z = –3.442, p = 0.001), ES (Z = –3.305, p = 0.001), DT (Z = –3.350, p = 0.001), and BR (Z = –3.761, p < 0.01). **c** SAT thickness sums D_I in females and males. Percentages (P) of fibrous structures (F) embedded in the SAT are also shown: $P = 100F/D_{I} = 100(D_I - D_E)/D_I$. There were significant differences between K_f and K_m in all variables: D_I (Z = –3.715, p < 0.01), D_E (Z = –3715, p < 0.01), and P (t (30) = 3.846, p = 0.001).

based on comprehensive data sets resulting from accurate and reliable measurements of body fat, is urgently needed for developing this important and complex topic of sports medicine.

Low fat reduces the ballast weight an athlete has to carry, but too low fat and body weight can cause severe health problems that may be associated with a performance breakdown [6, 13, 39–41]. The Working Group on Body Composition, Health and Performance, under the auspices of the IOC Medical Commission, has stated [6]: "A focus on low body weight and body fat content, combined with regulations in some weight-sensitive sports, are considered risk factors for extreme dieting, eating disorders and related health consequences among athletes.", and further: "Recently, a prospective controlled study showed that athletes who reported dieting or the desire to be leaner to improve performance are more likely to develop eating disorders [42, 43]. However, it is important to keep in mind that controlled, longitudinal studies are needed to examine the true risks and trigger factors…". Recently, the authors of one of the few available long-time studies stated that only 72 % of former elite athletes who suffered from eating disorders during their athletic career reported that they had recovered 15–20 years

▶ **Table 2** Comparison of a sub-group of nine athletes who were measured in Kenya (E1) and in Austria 18 weeks later (E2).

VARIABLE [UNIT]	$K_{m,E1}$ MEAN (± SD)	$K_{m,E2}$ MEAN (± SD)	test results
m **[kg]**	52.6 * (± 4.9)	53.6 * (± 4.4)	t (8) = −1.388, p = 0.203
BMI [kgm⁻²]	18.9 * (± 1.6)	19.2 * (± 1.5)	t (8) = −1.350, p = 0.214
MI_1 [kgm⁻²]	19.8 * (± 1.7)	20.2 * (± 1.6)	t (8) = −1.441, p = 0.188
SAT THICKNESS SUMS D_I and D_E [mm]; MEDIAN (IQR)			
D_I	6.1 (9.7)	7.0 * (12.0)	Z = −0.178, p = 0.859
D_E	3.2 (6.0)	4.3 * (9.1)	Z = −1.007, p = 0.314
SAT THICKNESSES AT INDIVIDUAL BODY SITES d_I [mm]; MEDIAN (IQR)			
$d_{I,UA}$	0.8 * (1.5)	1.6 * (1.3)	t (8) = −1.177, p = 0.273
$d_{I,LA}$	0.8 (2.9)	1.1 * (4.1)	Z = −1.125, p = 0.260
$d_{I,FT}$	1.0 * (1.9)	0.9 * (2.1)	t (8) = −0.494, p = 0.634
$d_{I,LT}$	0.2 (0.8)	0.2 (0.6)	Z = −0.296, p = 0.767
$d_{I,MC}$	0.4 (1.7)	1.0 * (1.4)	Z = −0.178, p = 0.859
$d_{I,ES}$	0.6 (1.5)	0.8 * (1.1)	Z = −0.296, p = 0.767
$d_{I,DT}$	1.2 * (2.1)	1.0 * (2.6)	t (8) = 0.879, p = 0.405
$d_{I,BR}$	0.2 * (0.4)	0.4 * (0.8)	t (8) = −1488, p = 0.175

Measurement series E1: Kenya, April 8–14, 2017; Measurement series E2: Austria, August 31 and September 1, 2017; Abbreviations: body mass (m), body mass index (BMI = m/h²), mass index (MI_1 = 0.53.m/(hs)), sum of the eight standardised subcutaneous adipose t**i**ssue (SAT) sites included (D_I) or **e**xcluded (D_E) embedded fibrous structures in the thickness values. Interquartile range (IQR), (UA) upper abdomen, (LA) lower abdomen, (FT) front thigh, (LT) lateral thigh, (MC) medial calf, (ES) erector spinae, (DT) distal triceps, and (BR) brachioradialis. Stars (*) mark normally distributed data where the paired t-test (t) was used. Wilcoxon test (Z) was used for not normally distributed data.

later [44]. The IOC Working Group states that there is a need for sport-specific and sex-specific preventive programs to establish recognised criteria for raising the alarm and no-start decisions for athletes with eating disorders, and points out the importance of developing standardised methods for body composition assessment. Meanwhile, in cooperation with the above mentioned IOC Working and Research Group, important steps have been made concerning the latter guideline: the US method for measuring SAT has been standardised [14] and tested within the framework of an international multi-centre study [16]. This method has also been tested in children [45].

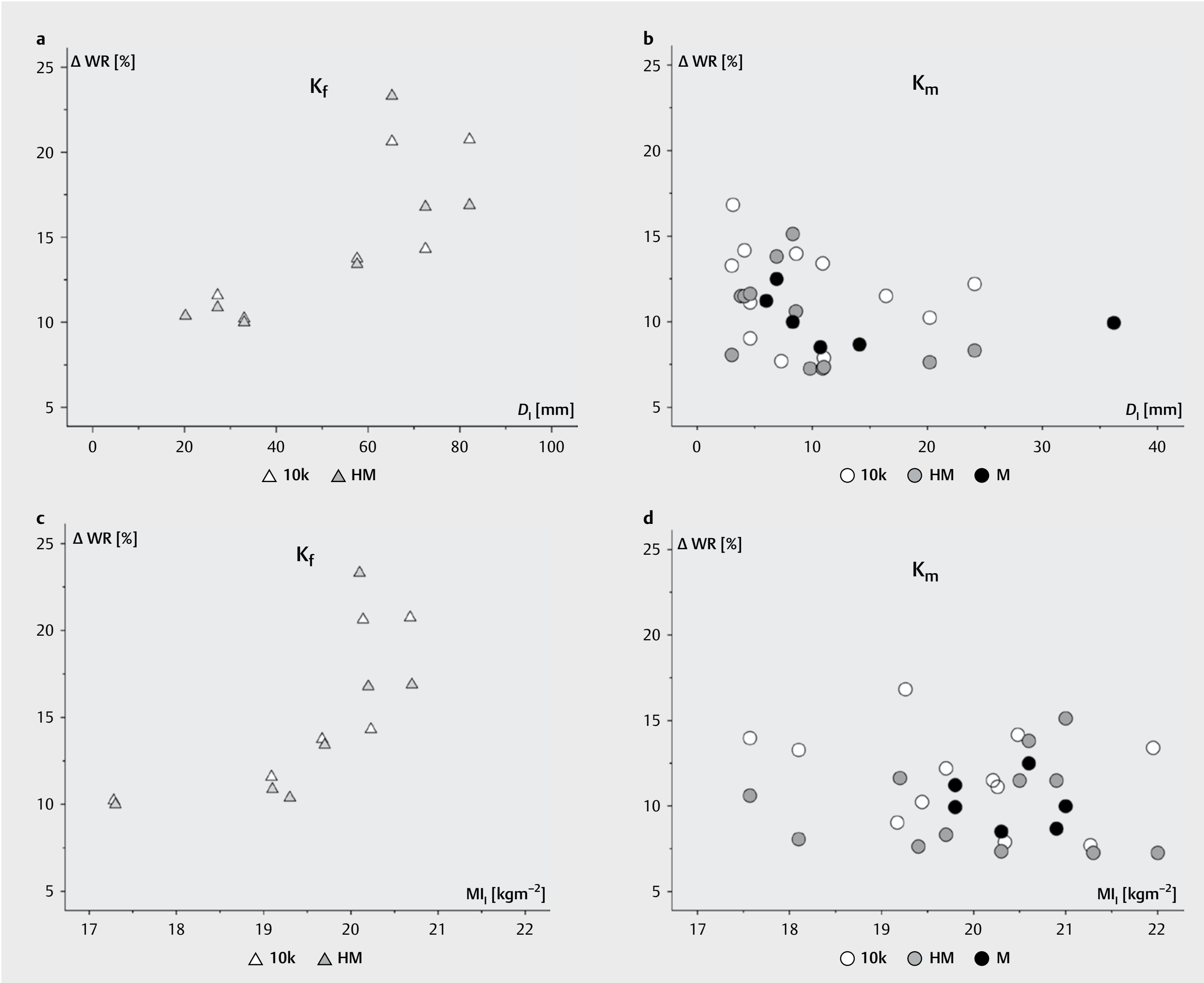
No significant differences in the amount of SAT were found when the body fat was measured a second time (4.5 months later) as can be seen in ▶ **Table 2** (comparisons of $K_{m,E1}$ and $K_{m,E2}$). This is not surprising because, when in Austria, they used the same traditional African diet cooked by themselves, and training volumes, intensities, and the campsite elevation were similar.

A detailed discussion of the complex physiological and pathophysiological functions of body fat can be found in Trayhurn P and Beattie JH 2001 [37], and in Wajchenberg BL 2000 [19]; a chapter on lipid metabolism in athletes can be found in Brooks GA et al. 2005 [46]. The over-all effects of training and food supply impact the athletes' physique, which is related to their performance. As we observed during the study in the camp, the traditional Kenyan diet is rich in carbohydrates, e. g., contained in the maize dish 'ugali', in fruits, rice, and potatoes. Meat and animal fat are rare. Alcohol is not permitted at all [47]. According to Wilber et al. [48], the Kenyan/Ethiopian diet consists of 77 % carbohydrate, 13 % fat, and 10 % protein.

Inadequate food availability, food insecurity due to cultural practices, or lack of financial resources may increase the risk of low energy availability and severe health and performance consequences may result [3, 5]. The standardised US method can capture the over-all effect of nutrition and training in terms of accurate SAT measurement, which represents the major part of (anatomically detectable) body fat. Changes in body composition can easily be traced accurately with the standardised US method in the field. This important information on the body composition status should routinely be used for both optimising the training and for raising the alarm when an athlete's body composition develops towards critically low values [3, 6, 28].

Competitive performance and relative body weight in Kenyan long-distance runners

▶ **Fig. 3e** shows that all athletes' MI_1-values were higher than their BMIs (the differences ranged from 0.3 to 1.7 kgm−²), indicating their longer legs (compared to ▶ **Table 1S** in the SM) when compared to Caucasian White groups [34]. Both BMI and MI_1 values of female (18.6 ± 0.9, 19.5 ± 1.1, respectively) and male participants (19.1 ± 1.2, 20.1 ± 1.2) were within a very narrow range (▶ **Fig. 2a** and **b**), but SAT thickness sums from the eight standardised sites (D_I) ranged in the female group from 20.2 to 82.1 mm (i. e., a factor of 4), and in the male group from 3.0 to 36.2 mm (i. e., a factor of 12). This indicates that long-distance runners (and their coaches) may have focused on the measure for relative body weight rather than on body fat content. One reason for this may be that they did not have an opportunity to measure fat accurately. BMI or MI_1 are not useful tools for assessing body composition in athletes as they cannot distinguish between fat and muscle mass: ▶ **Fig. 1**, for example, shows the upper abdomen (UA) images of two long-distance runners with almost the same BMI (19.0 kgm⁻², and 18.7 kgm⁻²) whose sums of SAT thicknesses D_I differed by 240 % (20.2 mm vs.



▶ **Fig. 5** Dependency of running performance on body fat (in terms of D_l) and on relative body weight (in terms of MI_1) The dependencies of performances on subcutaneous adipose tissue thickness sums (D_l) and on relative body weight (MI_1) are shown for the female (K_f; N = 7) and male (K_m; N = 25) groups. The athletes competed in marathon, or half marathon, or 10 km races, and some of them in two of these distances. Therefore, running performances are given in terms of percentual differences to the word record (WR): ΔWR [%] = 100 . (PB-WR)/WR. Were PB are the personal best times. In case of athletes participating in two disciplines, both running times were used for the correlation analysis. WR until September 2019: 10 km: females: 29:17,45; males: 26:17,54. Half marathon (HM): females: 1:04:51; males: 58:01. Marathon (M) females: 2:15:25; males: 2:01:39. **a** Female group K_f: There was a significant positive correlation between D_l and running performance in K_f ($r = 0.782$, $p = 0.002$), however, the PB times show that there was a larger performance range in the female group compared to the male group. In the subgroup with personal best times below or close to world record time plus 10 %, there was no correlation. **b** as in A, but for the group K_m. There was a (very) weak negative correlation between D_l and running performance in K_m ($r_s = -0.390$, $p = 0.033$). **c** Females group (K_f). Running performance and relative body weight. There was a significant correlation between these variables ($r_s = 0.835$, $p < 0.001$), however, the PB times show that there was a larger performance range in the female group compared to the male group. In the subgroup with PB times below or close to WR time plus 10 % (N = 3), there was no correlation. **d** as in C, but for group K_m. There was no significant correlation between ΔWR and MI_1 ($r_s = -0.152$, $p = 0.424$).

6.0 mm). In the female group (▶ **Fig. 5c**), there was a significant correlation between relative body weight (in terms of both MI_1 and BMI) and performance (quantified as ΔWR), although the BMI range was small. One reason for this may be that the performance heterogeneity was larger in the female group. Furthermore, data should be interpreted with caution because the number of female athletes was only seven. In contrast to the female group, no correlation was found in the male group (▶ **Fig. 5d**) that showed a higher performance homogeneity (95 % of the 20 athletes had PB times below WR plus 15 %, and 50 % had PB times below WR plus 10 %).

This indicates that differences between athletes in BMI (or MI_1), within the narrow range found in this group, cannot be seen as a performance criterion. Mooses et al. [35] stated in their review paper that BMI values of East African female runners were between 16.9 and 19.9 kgm^{-2}, and between 18.3 and 20.8 kgm^{-2} for male runners. Marc et al. [49] showed that the body mass and the BMI of the 100 best male marathon runners decreased significantly between 1990 and 2011 (m: from 59.6 ± 2.3 kg in 1990 to 56.2 ± 1.1 kg in 2011; BMI: from 19.8 ± 1.7 kgm^{-2} in 1990 to 19.4 ± 1.3 kgm^{-2} in 2011). In the study presented here, the mean body mass, and the mean BMI of male participants were even lower: (m: 54.0 ± 4.3 kg; BMI: 19.1 ± 1.2 kgm^{-2}). In other sports, e. g. in ski jumping [25–27], the development towards extremely low body weight was associated with severe health problems that made changes to the regulations necessary ('BMI-rule') to prevent further cases of anorexia nervosa. The mean BMI-values found in long-distance running in the current study and in the publications cited above show similarly low values as were found in ski jumping [27]: this possibly marks a dangerous development towards increased health hazards, however, in the group of Kenyan runners, the MI_1 values are higher than the BMIs.

It is important to point out that we did not find an indication that lower body mass or lower body fat were associated with significantly higher performance in these athletes: this should be considered when discussing questions of 'optimal body composition'. It is imaginable that PB times might increase when those who have comparatively much body fat would increase their muscle/fat ratio without reducing their relative body weight. However, longitudinal studies are not available because sufficiently sensitive body fat measurement techniques were missing.

When applying the WHO criterion for 'underweight' (BMI less than 18.5 kgm^{-2}) [36] to the long-distance runners studied here, ten athletes are to be classified as underweight (males and females together), and four of them (three males and one female) were even below 17.5 kgm^{-2} (which is used as one of the four criteria for diagnosing anorexia nervosa [33]). When using the MI_1 instead of the BMI, only four athletes are 'underweight', and only one (female) athlete was below MI_1 = 17.5 kgm^{-2}. For persons with long legs, the BMI is misleading: "*Problems arise, however, in adults whose shape differs from the norm, particularly those whose legs are shorter or longer than might be expected for their height* " [24]. The MI_1 considers the body proportions and is, therefore, a better measure for relative body weight than the BMI. The MI_1 is defined such that the BMI cut-off values according to the WHO criteria [36] for underweight (18.5 kgm^{-2}), overweight (25.0 kgm^{-2}), and obesity (30.0 kgm^{-2}) can remain the same. This holds also true for the threshold value of 17.5 kgm^{-2} used as a diagnostic criterion for anorexia nervosa [33].

Subcutaneous fat patterning in elite Kenyan long-distance runners

Additionally, to the sums of SAT thicknesses, information contained in the fat patterning may be important for performance analyses of elite long-distance runners because the distribution of the SAT influences the biomechanical aspects of running economy. Any additional fat mass on the legs and arms has to be accelerated to a speed much higher than the running speed and slowed down again at every step. This costs more energy than the much lower accelerations of the same amount of ballast mass on the trunk; however, wobbling masses can reduce the metabolic costs of active impact reduction [21].Therefore, it is of interest to compare the amounts of SAT found on the trunk (mean on trunk: T_{MEAN}) represented by UA, LA, and ES, and on the legs plus arms (mean on extremities E_{MEAN}) represented by FT, LT, MC, DT, and BR. The ratio E_{MEAN}/T_{MEAN} of 1.21 (± 0.89) of male participants was significantly lower (Z = –2.393; p = 0.017) compared to the ratio E_{MEAN}/T_{MEAN} of 1.79 (± 0.75) in their female counterparts. This indicates that the women investigated in this study had to accelerate a higher percentage of fat mass situated on their legs and arms, which may necessitate a higher power compared to the men's group (at the same running speed). Additionally, all thicknesses at the eight individual measurement sites (as well as their sum totals) were substantially higher in women than in men. Based on the data presented here, biomechanical modelling of endurance running could analyse these effects in quantitative way. Energy dissipation and damping effects in running due to wobbling masses have been studied already, and this wobbling mass model [21, 50] could be applied to the ratios and fat amounts found here. Detailed information on the fat patterning is presented in the SM. The patterning ratios found in this study are in line with previous findings in another sport: in Judo, there was also a significant difference (Z = –3.394; p = 0.001) between the E_{MEAN}/T_{MEAN} ratios in female 2.21 (± 0.85)) and male elite athletes: 1.24 (± 0.61). In Judo, the ratio in the men's group was almost the same as in the long-distance runners from Kenya. The female judokas had significantly larger fat amounts on their legs than the male judokas. However, the ratio of E_{MEAN}/T_{MEAN} in the female judoka group was much larger than in the female long-distance runners. This indicates that lower fat amounts on the legs may be a crucial parameter for running performance.

Conclusions and Perspectives

Ranges of body fat in female and male athletes

In the female group (N = 7), body fat, represented by SAT thickness sums D_I and D_E, showed a very wide range from D_I = 20.2 to 82.1 mm, and D_E = 14.0 to 75.3 mm (reliability of the method: ± 1 mm, i. e. ± 0.2 kg changes can be monitored), but there were also large differences in performance (PB times ranged from WR plus 10 % to WR plus 23 %). The best three females' runners (close to WR plus 10 %) had D_I values of 20.2 mm ('extremely low', according to preliminary normative [28]), 27.2 mm ('very low'), and 33.0 mm ('very low'), their mean D_I was 26.8 mm.

In the male group (N = 19; PB better than WR plus 15 %), D_I ranged from 3.0 to 36.2 mm, and D_E from 2.3 to 28.0 mm. The three male athletes with the highest fat amount (D_I: 20.5, 24.1, and 36.2 mm; mean: 26.9 mm) had similar values as the three best women, and these male runners were among the best ones of the male group. Despite higher energy costs for accelerating the fat ballast mass, this may be explained because fat metabolism plays a crucial role in endurance sports, has important endocrine functions, and energy dissipation –due to wobbling masses– may also play a role. However, there was an accumulation at the very low fat edge: 17 male athletes had D_I-values below 12 mm, which is 'extremely low' according to preliminary normative data for male athletes [28].

Body fat should not only be seen as ballast mass: it should be considered that extremely low fat levels may be disadvantageous for both health and performance.

Measures of relative body mass

Many African ethnic groups are known to have longer legs compared to Caucasian persons [34, 51], which resulted in MI_1 values higher than BMIs in all participants. The mean difference MI_1-BMI was 0.9 kgm^{-2}, ranging from 0.3 to 1.7 kgm^{-2}. According to the WHO cut-off value (18.5 kgm^{-2}), only four athletes were 'underweight' when using MI_1, whereas ten would be appraised to be 'underweight' when using the BMI (which does not consider leg length).

Correlation of relative body mass (in terms of MI_1 and BMI) with performance

BMI and MI_1 values of female (18.6 ± 0.9, 19.5 ± 1.1, respectively) and male participants (19.1 ± 1.2, 20.1 ± 1.2) were within a narrow range, although SAT thickness sums D_I ranged from 20.2 to 82.1 mm in the female group, and from 3.0 to 36.2 mm in the male group. In the groups of female and male runners whose PB times were below or close to WR plus 10 %, there was no correlation between BMI or MI_1 and performance, and this holds also true for the whole male group (PB times below WR time plus 15 %).

Correlation between body fat and performance

In the whole male group (N = 19; performance better than WR time plus 15 %) and in the male subgroup (WR plus 10 %), higher body fat (in terms of D_I and D_E) was not associated with lower performance. The performance of the best three females (WR plus about 10 %) also did not show a dependency between performance and D_I or D_E. This indicates that different elite athletes may need different body fat amounts for optimising their individual performance. For the whole group of females (N = 7), there was a significant positive correlation, but this should be interpreted with caution because of the low number of participants and the performance heterogeneity.

Differences in fibrous structures (fascias) between sexes

The sexual dimorphism in body fat in terms of D_E (for the medians, the ratio was: 49.6mm/6.7mm = 7.4) was larger than in terms of D_I (57.6/8.6 = 6.7) because women had a lower amount of fibrous structures (fascias) embedded in the SAT. The percentage of these fibrous structures with respect to the thickness D_I was 13.9 % in women and 29.5 % in men. Lower amounts of embedded fibrous structures in women than in men were also found in elite judokas (8.6 %, and 20.2 %, respectively) [29], and in a mixed group of 76 elite athletes measured in five independent research centres (11 %, and 18 %, respectively) [16].

Fat patterning: SAT on extremity and trunk

The ratios of SAT found on the extremities (E_{MEAN}: mean of the sites FT, LT, MC, DT, and BR) to SAT on the trunk (T_{MEAN}: mean of UA, LA, and ES) were larger in women than in men: E_{MEAN}/T_{MEAN} was 1.79 and 1.21, respectively. Previously, larger ratios in women than in men were also found in a group of judokas (2.21 vs. 1.24) [29], but the ratios were higher in the group of Kenyan female long-distance runners. Low fat on the legs may be a crucial parameter for running performance; but models mimicking elite athletes with their fat patterning have not yet been published.

Acknowledgements

We thank all athletes for their participation, and the running association run2gether, particularly director T. Krejci for the excellent cooperation. Further, we thank the directors W. Gotschke and C. Toth (Leistungssport Austria), and the former IMSB-Austria director H. Holdhaus for supporting the measurements in 2017. We thank Timothy A. Ackland for his constructive comments on the manuscript. Further, we thank the Doctoral School of the Medical University of Graz for partially providing the publication costs. Results of the study are presented clearly, honestly and without fabrication, falsification, or inappropriate data manipulation.

Conflict of Interest

WM and AF contributed to the software development and may participate in the returns. The other authors declare that there are no conflicts of interest.

References

[1] Slater G, O'Connor H, Kerr A. Optimising physique for sports performance. In: Hume P, Kerr DA, Ackland TR, (Eds). Best Practice Protocols for Physique Assessment in Sport. Springer Nature Singapore; 2018: 27–36. doi:10.1007/978-981-10-5418-1_3

[2] Ackland TR, Lohman TG, Sundgot-Borgen J et al. Current status of body composition assessment in sport: review and position statement on behalf of the ad hoc research working group on body composition health and performance, under the auspices of the I.O.C. Medical Commission. Sports Med 2012; 42: 227–249. doi:10.2165/11597140-000000000-00000

[3] Burke LM, Close GL, Lundy B et al. Relative energy deficiency in sport in male athletes: A commentary on its presentation among selected groups of male athletes. Int J Sport Nutr Exerc Metab 2018; 28: 364–374. doi:10.1123/ijsnem.2018-0182

[4] Tornberg AB, Melin A, Koivula FM et al. Reduced neuromuscular performance in amenorrheic elite endurance athletes. Med Sci Sports Exerc 2017; 49: 2478–2485. doi:10.1249/MSS.0000000000001383

[5] Mountjoy M, Sundgot-Borgen J, Burke L et al. International Olympic Committee (IOC) Consensus Statement on Relative Energy Deficiency in Sport (RED-S): 2018 Update. Int J Sport Nutr Exerc Metab 2018; 28: 316–331. doi:10.1123/ijsnem.2018-0136

[6] Sundgot-Borgen J, Meyer NL, Lohman TG et al. How to minimise the health risks to athletes who compete in weight-sensitive sports review and position statement on behalf of the Ad Hoc Research Working Group on Body Composition, Health and Performance, under the auspices of the IOC Medical Commission. Br J Sports Med 2013; 47: 1012–1022. doi:10.1136/bjsports-2013-092966

[7] Meyer NL, Sundgot-Borgen J, Lohman TG et al. Body composition for health and performance: a survey of body composition assessment practice carried out by the Ad Hoc Research Working Group on Body Composition, Health and Performance under the auspices of the IOC Medical Commission. Br J Sports Med 2013; 47: 1044–1053. doi:10.1136/bjsports-2013-092561

[8] Hume P, Kerr D, Ackland TR. Best Practice Protocols for Physique Assessment in Sport. Springer; Singapore: 2018. doi:10.1007/978-981-10-5418-1

[9] Adams J, Mottola M, Bagnall KM et al. Total body fat content in a group of professional football players. Can J Appl Sport Sci 1982; 7: 36–40

[10] Stewart AD, Hannan WJ. Prediction of fat and fat-free mass in male athletes using dual X-ray absorptiometry as the reference method. J Sports Sci 2000; 18: 263–274. doi:10.1080/026404100365009

[11] Müller W, Horn M, Fürhapter-Rieger A et al. Body composition in sport: Interobserver reliability of a novel ultrasound measure of subcutaneous fat tissue. Br J Sports Med 2013; 47: 1036–1043. doi:10.1136/bjsports-2013-092233

[12] Müller W, Horn M, Fürhapter-Rieger A et al. Body composition in sport: A comparison of a novel ultrasound imaging technique to measure subcutaneous fat tissue compared with skinfold measurement. Br J Sports Med 2013; 47: 1028–1035. doi:10.1136/bjsports-2013-092232

[13] Müller W, Maughan RJ. The need for a novel approach to measure body composition: Is ultrasound an answer? Br J Sports Med 2013; 47: 1001–1002. doi:10.1136/bjsports-2013-092882

[14] Müller W, Lohman TG, Stewart AD et al. Subcutaneous fat patterning in athletes: selection of appropriate sites and standardisation of a novel ultrasound measurement technique: ad hoc working group on body composition, health and performance, under the auspices of the IOC Medical Commission. Br J Sports Med 2016; 50: 45–54. doi:10.1136/bjsports-2015-095641

[15] Störchle P, Müller W, Sengeis M et al. Standardized ultrasound measurement of subcutaneous fat patterning: High reliability and accuracy in groups ranging from lean to obese. Ultrasound Med Biol 2017; 43: 427–438. doi:10.1016/j.ultrasmedbio.2016.09.014

[16] Müller W, Fürhapter-Rieger A, Ahammer H et al. Relative body weight and standardised brightness-mode ultrasound measurement of subcutaneous fat in athletes: An international multicentre reliability study, under the auspices of the IOC medical Commission. Sports Med 2020; 50: 597–614. doi:10.1007/s40279-019-01192-9

[17] Lackner S, Mörkl S, Müller W et al. Novel approaches for the assessment of relative body weight and body fat in diagnosis and treatment of anorexia nervosa: A cross-sectional study. Clin Nutr 2019; 38: 2913–2921. doi:10.1016/j.clnu.2018.12.031

[18] Abe T, Loenneke JP, Thiebaud RS. An ultrasound prediction equation to estimate DXA-derived body fatness for middle-aged and older caucasian adults. J Frailty Aging 2019; 8: 79–84. doi:10.14283/jfa.2019.8

[19] Wajchenberg BL. Subcutaneous and visceral adipose tissue: Their relation to the metabolic syndrome. Endocr Rev 2000; 21: 697–738. doi:10.1210/edrv.21.6.0415

[20] Herman IP. Sound, speech, and hearing. In: Physics of the Human Body. 2nd Edition. Switzerland: Springer International; 2016: 657–730

[21] Schmitt S, Günther M. Human leg impact: Energy dissipation of wobbling masses. Arch Appl Mech 2011; 81: 887–897. doi:10.1007/s00419-010-0458-z

[22] Brooks GA, Fahey TD, Baldwin KM. Exercise Physiology: Human Bioenergetics and Its Applications. New York: McGraw-Hill; 2005: 154

[23] Nattiv A, Lynch L. The female athlete triad. Phys Sportsmed 1994; 22: 60–68. doi:10.1080/00913847.1994.11710446

[24] World Health Organization (WHO). Physical Status: The Use and Interpretation of Anthropometry. Report of a WHO Expert Committee. In, World Health Organization technical report series. 1995/01/01 ed 1995: 355

[25] Müller W. Determinants of ski-jump performance and implications for health, safety and fairness. Sports Med 2009; 39: 85–106. doi:10.2165/00007256-200939020-00001

[26] Müller W. Towards research-based approaches for solving body composition problems in sports: Ski jumping as a heuristic example. Br J Sports Med 2009; 43: 1013–1019 doi:10.1136/bjsm.2009.068775

[27] Müller W, Gröschl W, Müller R et al. Underweight in ski jumping: The solution of the problem. Int J Sports Med 2006; 27: 926–934. doi:10.1055/s-2006-923844

[28] Ackland TR, Müller W. Imaging method: Ultrasound. In: Hume PA, Kerr DA, Ackland TR, (Eds). Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer; 2018: 131–141

[29] Sengeis M, Müller W, Störchle P et al. Body weight and subcutaneous fat patterning in elite judokas. Scand J Med Sci Sports 2019; 29: 1774–1788. doi:10.1111/sms.13508

[30] Kelso A, Trajer E, Machus K et al. Assessment of subcutaneous adipose tissue using ultrasound in highly trained junior rowers. Eur J Sports Sci 2017; 17: 576–585. doi:10.1080/17461391.2016.1277788

[31] Harriss DJ, MacSween A, Atkinson G. Ethical standards in sport and exercise science research: 2020 update. Int J Sports Med 2019; 40: 813–817. doi:10.1055/a-1015-3123

[32] Stewart AD, Marfell-Jones M, Olds T et al. International Standards for Anthropometric Assessment. Lower Hutt, New Zealand: International Society for the Advancement of Kinanthropometry; 2011

[33] In. World Health Organisation. International statistical classification of diseases and related health problems, 10th revision, Fifth edition. World Health Organisation; 2016. Available at https://apps.who.int/iris/handle/10665/246208

[34] Larsen HB, Christensen DL, Nolan T et al. Body dimensions, exercise capacity and physical activity level of adolescent Nandi boys in western Kenya. Ann Hum Biol 2004; 31: 159–173. doi:10.1080/03014460410001663416

[35] Mooses M, Hackney AC. Anthropometrics and body composition in east african runners: Potential impact on performance. Int J Sports Physiol Perform 2017; 12: 422–430. doi:10.1123/ijspp.2016-0408

[36] World Health Organization (WHO). Physical status: The use and interpretation of anthropometry. Report of a WHO Expert Committee. World Health Organization Technical Report Series; 1995; 854: 329

[37] Trayhurn P, Beattie JH. Physiological role of adipose tissue: White adipose tissue as an endocrine and secretory organ. Proc Nutr Soc 2001; 60: 329–339. doi:10.1079/pns200194

[38] Hamilton B. East African running dominance: what is behind it? Br J Sports Med 2000; 34: 391–394

[39] Nattiv A, Loucks AB, Manore MM et al. American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc 2007; 39: 1867–1882. doi:10.1249/mss.0b013e318149f111

[40] Becker AE, Grinspoon SK, Klibanski A et al. Eating disorders. N Engl J Med 1999; 340: 1092–1098. doi:10.1056/nejm199904083401407

[41] Sullivan PF. Mortality in anorexia nervosa. Am J Psychiatry 1995; 152: 1073–1074. doi:10.1176/ajp.152.7.1073

[42] Martinsen M, Bahr R, Børresen R et al. Preventing eating disorders among young elite athletes: a randomized controlled trial. Med Sci Sports Exerc 2014; 46: 435–447

[43] Martinsen M, Sundgot-Borgen J. Higher prevalence of eating disorders among adolescent elite athletes than controls. Med Sci Sports Exerc 2013; 45: 1188–1197

[44] Sundgot-Borgen J, Danielsen KK, Torstveit MK. Female former elite athletes suffering from eating disorders during their career. A 15-20 year follow-up. Med Sci Sports Exerc 2012; 44(5S): 703

[45] Kelso A, Müller W, Fürhapter-Rieger A et al. High inter-observer reliability in standardized ultrasound measurements of subcutaneous adipose tissue in children aged three to six years. BMC Pediatr 2020; 20: 145. doi:10.1186/s12887-020-02044-6

[46] Brooks GA, Fahey TD, Baldwin KM. Exercise Physiology: Human Bioenergetics and Its Applications. New York: McGraw-Hill; 2005: 124–154

[47] gether Run, Krejci T.. Running wonderland. In. 2019; https://run2gether.com/?portfolio=things-to-know&lang=en#tab-id-3

[48] Wilber RL, Pitsiladis YP. Kenyan and Ethiopian distance runners: What makes them so good? Int J Sports Physiol Perform 2012; 7: 92–102

[49] Marc A, Sedeaud A, Guillaume M et al. Marathon progress: Demography, morphology and environment. J Sports Sci 2014; 32: 524–532. doi:10.1080/02640414.2013.835436

[50] Gruber K, Ruder H, Denoth J et al. A comparative study of impact dynamics: wobbling mass model versus rigid body models. J Biomech 1998; 31: 439–444. doi:10.1016/s0021-9290(98)00033-5

[51] Norgan NG. Population differences in body composition in relation to the body mass index. Eur J Clin Nutr 1994; 48: Suppl 3: S10–S25. discussion S26-7