Dissertation

ANTHROPOMETRY AND SUBCUTANEOUS ADIPOSE TISSUE PATTERNING IN ELITE ATHLETES: APPLICATION OF A NOVEL ULTRASOUND METHOD

submitted by

Mag.^{a} rer. nat.

Marietta SENGEIS

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Univ.-Prof. Mag.rer.nat. Dr. phil. Wolfram MÜLLER

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Statutory Declaration

I hereby declare that this thesis is my own original work and that I have fully acknowledged by name all those individuals and organisations that have contributed to the research for this thesis. Due acknowledgement has been made in the text to all other material used. Throughout this thesis and in all related publications I followed the Standards of Good Scientific Practice and Ombud Committee at the Medical University of Graz.

List of Peer Reviewed Publications of the Author that are Related to this Thesis.

Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. PMID: 33053598.

Sengeis M, Müller W, Störchle P, Führhapter-Rieger A. Body weight and subcutaneous fat patterning in elite judokas. Scand J Med Sci Sports. 2019 Nov;29(11):1774-1788. doi: 10.1111/sms.13508. Epub 2019 Jul 17. PMID: 31265152; PMCID: PMC6851779.

Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Ultrasound technique: a new approach for measuring subcutaneous adipose tissue in endurance athletes. Deutscher Olympischer Sportärztekongress. May 26-28, 2018.

Sengeis M, Störchle P, Müller W. The BMI is not a useful measure for body fat: a comparison with ultrasound subcutaneous adipose tissue measurements. 17. ÖGE Jahrestagung 2017-Nachhaltigkeit. Nov 9-10, 2017; Vienna, Austria.

Sengeis M, Müller W, Störchle P, Führhapter-Rieger A. Somatotyping and Subcutaneous Adipose Tissue Patterning Using the Novel Ultrasound Measurement Technique in Male and Female Elite Judokas. In: Sertić H, Čorak S, Segedi I, editors. Proceedings Book: Applicable Research in Judo. Faculty of Kinesiology, University of Zagreb, Croatia. Jun 20-21, 2016. ISBN: 978-953-317-044-2.

List of Peer Reviewed Journal Publications as a Co-Author.

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Cardio-Metabolic Risk in Children and Adolescents. Biology 2021, 10, 449. https://doi.org/10.3390/biology10050449.

Kelso A, Müller W, Fürhapter-Rieger A, **Sengeis M**, Ahammer H, Steinacker JM. High inter-observer reliability in standardized ultrasound measurements of subcutaneous adipose tissue in children aged three to six years. BMC Pediatr. 2020 Apr 2;20(1):145. doi: 10.1186/s12887-020-02044-6. PMID: 32241257; PMCID: PMC7114789.

Störchle P, Müller W, **Sengeis M**, Lackner S, Holasek S, Fürhapter-Rieger A. Measurement of mean subcutaneous fat thickness: eight standardised ultrasound sites compared to 216 randomly selected sites. Sci Rep. 2018 Nov 2;8(1):16268. doi: 10.1038/s41598-018-34213-0. PMID: 30389952; PMCID: PMC6214952.

Störchle P, Müller W, **Sengeis M**, Ahammer H, Fürhapter-Rieger A, Bachl N, Lackner S, Mörkl S, Holasek S. Standardized Ultrasound Measurement of Subcutaneous Fat Patterning: High Reliability and Accuracy in Groups Ranging from Lean to Obese. Ultrasound Med Biol. 2017 Feb;43:427-438. doi: 10.1016/j.ultrasmedbio.2016.09.014. Epub 2016 Nov 18. PMID: 27866704.

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Parts of this thesis were published in:

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All co-authors, Alfred Fürhapter-Rieger, Wolfram Müller, and Paul Störchle, have approved the use of the data of these publications in this thesis.

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Abbreviations

I	Included; indicates that the fibrous structures are included in the SAT thickness value
E	Excluded; indicates that the fibrous structures embedded in the SAT are not included in the thickness value
F	Sum of thicknesses (of eight sites) of embedded fibrous structures
P	Percentage of fibrous structures (F) embedded in the SAT
ROI	Region of interest
SAT	Subcutaneous adipose tissue
US	Ultrasound
WR	World record in the marathon, half marathon, and 10 km
PB	Personal best in represented disciplines
ΔWR [%]	$100 \cdot (PB - WR)/WR$

Parameters and variables:

a	Age, in years
b	Biceps girth flexed and tensed, in m
BMI	Body mass index: BMI= $\frac{m}{h^2}$, in kg m^{-2}
C	Cormic index: s/h, in m
d	SAT thickness at a given site, in millimetres (this is the average of the distances measured in a given US image within the ROI), in mm
D	Sum of SAT thicknesses of all eight sites in a given participant, in mm
g	Gluteal (hip) girth, in m
h	Stature, in m
IASMS	International Association of Sciences in Medicine and Sports
ISAK	International Society for the Advancement of Kinanthropometry
l	Leg length, in m
L	Leg-to-height ratio (l/h)
m	Body mass, in kg
MI_1	Mass index: $\mathrm{MI}_1 = 0.53\frac{m}{hs}$, in, kg m^{-2}
s	Sitting height, in m
SF	Skinfold sites according to ISAK: triceps, subscapular, biceps, supraspinale, iliac crest, abdominal, front thigh, medial calf
SF_8	Sum of skinfolds at all eight ISAK sites in a given participant, in mm
t	Thigh girth at the site front thigh, in m
w	Waist girth, in m
X	Skinfold thickness at a given site, in mm
W	Waist-to-height ratio (w/h)

Statistics:

MEAN	Mean value
MEDIAN	Median value

N	Number of participants
r	Correlation coefficient
SD	Standard deviation
ρ	Spearman's rank correlation coefficient (Spearman's rho or denoted by r_s)

US Sites:	(UA) upper abdomen, (LA) lower abdomen, (FT) front thigh, (LT) lateral thigh, (MC) medial calf, (ES) erector spinae, (DT) distal triceps, (BR) brachioradialis

Participants and groups:

Af	All female athletes (N=105)
Am	All male athletes (N=167)

Judokas:

EO	European Open, internation competition in Oberwart Men: February 16-17, 2018, and Woman February 15, 2019.
G, G_f, G_m	Group: all participants, all females, all males
$G_{f,A}$	Group: female adults ≥18 years, excluding heavyweight category +78 kg
$G_{m,A}$	Group: male adults ≥18 years, excluding heavyweight category +100 kg
$G_{f,HW}$	Group: female heavyweights +78 kg and youth +70 kg
$G_{m,HW}$	Group: male heavyweights +100 kg
$G_{f,Y}$, $G_{m,Y}$	Group: female youth <18 years, male youth <18 years (excluding heavyweight category +70 kg for youth females, +100 kg for youth males)
$G_{f,A,1\text{-}5}$	Female adults groups 1 to 5 (excluding heavyweight, 7, and half-heavyweight, 6)
$G_{m,A,1\text{-}5}$	Male adults groups 1 to 5 (excl.heavyweight, 7, and half-heavyweight, 6)
$G_{f,A,6\text{-}7}$	Female adults groups 6 to 7 (heavyweight, 7, and half-heavyweight, 6)
$G_{m,A,6\text{-}7}$	Male adults groups 6 to 7 (heavyweight, 7, and half-heavyweight, 6)
J1	Judoka 1 (black column Figure 10)
J2	Judoka 2 (grey column Figure 10)
$J_{f,TC}$	Sub-group of female Judokas measured during an international training camp (January 7–9, 2016 in Mittersill, Austria), or in season.
$J_{f,EO}$	Sub-group of female Judokas measured on the day before the official weigh-in for an international competition (European Open Oberwart, February 16, 2019).
TC	International training camp (January 7–9, 2016 in Mittersill, Austria)
WC	Weight category

Kenyan long-distance runners:

E1	Examination one: April 8–14, 2017; Sports & Recreation Centre Mont Longonot Kyambogo, Kenya, 2380 m altitude
E2	Examination two: August 31–September 1, 2017; Turrach, Austria, 1600m altitude
K_f, K_m	Female and male Kenyan elite long-distance runners
K_{mE1}, K_{mE2}	Kenyan elite male long-distance runners at E1 and E2

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Zusammenfassung

Hintergrund:

Körpergewicht, relatives Körpergewicht und Fett sind im Hochleistungssport aufgrund der Auswirkungen auf die Leistung von großer Bedeutung. Spitzensportler und Spitzensportlerinnen wenden häufig extreme Methoden an, um die Körpermasse innerhalb weniger Tage zu reduzieren oder versuchen absichtlich oder unabsichtlich eine niedrige Körpermasse beizubehalten, ohne langfristige gesundheitliche Probleme zu berücksichtigen. Eine neuartige Ultraschall (US) Messmethode zur Erfassung von subkutanen Fettschichtdicken (SAT) wurde kürzlich entwickelt. Die Messgenauigkeit und hohe Wiederholgenauigkeit dieser standardisierten Methodik erlaubt es, SAT Messungen von Spitzensportlern und Spitzensportlerinnen zu beurteilen, zu vergleichen und Änderungen der Fettmasse ab 0,2 kg verlässlich zu detektieren.

Methoden:

Insgesamt wurden 272 erwachsene Spitzensportler und Spitzensportlerinnen (39 % Frauen und 61 % Männer) aus elf Sportarten inkludiert. Das Körpergewicht, die Körpergröße, Umfänge sowie SAT Dicken wurden gemessen. Weiters wurde der Body-Mass-Index ($BMI = (m/h^2$) und der Mass-Index ($MI_1 = 0.53\ m/(hs)$) bestimmt (*m*: Körpermasse, h: Körpergröße, *s*: Sitzgröße). Methodenvergleiche zwischen der häufig angewandten Hautfaltendickenmessung (SF) und SAT Dicken mittels US wurde bei Elite Judokas (N=61) durchgeführt.

Ergebnisse:

Die SAT−Summen der acht Stellen (D_I) waren bei Frauen typisch dreimal höher im Vergleich zu Männern (72,5 mm vs. 24,0 mm). Die eingebetteten Faserstrukturen im SAT bei Frauen (8,7 %) waren niedriger verglichen mit Männern (21,1 %) und die Fettverteilung zeigte signifikante Unterschiede: an allen acht Messstellen hatten Sportlerinnen höhere SAT Dicken. Das größte Verhältnis zwischen Frauen und Männern wurde bei allen untersuchten Gruppen am äußeren Oberschenkel (lateral thigh: 5,5) gefunden. Bei Vergleichen der Summenwerte D_I von Sportlerinnen und Sportlern derselben Sportart wurden die höchsten Unterschiede zwischen Frauen und Männern bei Langstreckenläufern gemessen (6,7). Vergleiche zwischen SFs und US wurde bei der Gruppe ‘Elite Judokas‘ untersucht. Die SF-Summen und US-Summen von zwei Judokas mit nahezu gleichen SF-Summen (44,9 mm versus 45,4 mm) unterschieden sich um einen Faktor vier (20,0 mm versus 5,1 mm) bei

Anwendung von US. Das relative Körpergewicht (BMI und MI_1) korrelierte nicht mit D_I in der Gruppe ‘Elite Judokas‘. Bei der Vermessung von weiblichen Judokas am Tag der offiziellen Abwaage vor einem internationalen Wettkampf zeigte sich kein signifikanter Zusammenhang zwischen der gewählten Gewichtsklasse (WC) (WC 48 kg oder weniger bis 70 kg oder weniger) und dem D_I (r_s = 0,107, p = 0,769). Bezüglich kenianischer Langstreckenläufer und Langstreckenläuferinnen lagen beide Maße für das relative Körpergewicht (BMI und MI_1) innerhalb eines engen Bereichs, jedoch mit großen Abweichungen des D_I.

Conclusio:

Die standardisierte US-Methodik kann zur Beurteilung des Subkutan-Fettes bei hochtrainierten Sportlern und Sportlerinnen auf dem im Spitzensport erforderlichen Genauigkeitsniveau verwendet werden. SF-Messungen, die eine Doppelschicht von SAT inklusive einer doppelten Hautschicht in einem undefiniert komprimierten Zustand erfassen, zeigten große Abweichungen zu den Ultraschallmessungen. Die Analyse des Subkutan-Fettes mit US zeigte typisch dreimal höhere Werte bei Frauen, wobei die eingebetteten Faszien bei Frauen niedriger waren, verglichen mit Männern. Die gemessenen acht SAT-Dicken bei den Frauen waren signifikant höher. Das relative Körpergewicht (BMI und MI_1) korrelierte nicht mit dem D_I in der Gruppe ‘Elite Judokas‘. BMI und MI_1 lagen bei kenianischen Langstreckenläufern und Langstreckenläuferinnen innerhalb eines engen Bereichs, die D_I Werte zeigten aber eine sehr große Bandbreite. Für die sportmedizinische Betreuung von Athleten ist die genaue Kenntnis der Körperzusammensetzung wesentlich, um auf mögliche Untergewichts-Probleme rechtzeitig hinweisen zu können.

Abstract

Introduction:

Body mass, relative body weight and fat are important in high-performance sports and especially weight-sensitive sports due to their impact on performance. Elite athletes often use extreme methods to reduce body mass within a few days (e.g., ‘weight cutting’ in combat sports) or try to intentionally or unintentionally maintain low body mass without considering long-term health problems. A novel ultrasound (US) B-mode measurement method for measuring subcutaneous adipose tissue (SAT) thicknesses at eight standardised body sites has recently been introduced. This method enables to measure body fat (in terms of SAT) of elite athletes of various sports with their different physiques on an accuracy level not reached by any other method: SAT mass changes as low as 0.2 kg can be detected reliably.

Methods:

A total of 272 adult elite athletes (39 % females, and 61 % males) involved in eleven sports from fourteen countries were evaluated. Anthropometric variables, and measures of SAT thicknesses at eight defined body sites were taken. Relative body weight in terms of body mass index ($BMI = m/h^2$), and mass index ($MI_1 = 0.53\, m/(hs)$) were determined (h: stature, s: sitting height, m: body mass). Comparisons of skinfolds (SF) and US results were analysed in elite judokas (N=61).

Results:

Medians of SAT thickness sums in terms of D_{I} were about three times higher in females compared with males (72.5 mm vs 24.0 mm), whereas the median percentage of embedded fibrous structures in the SAT was lower in females (8.7 %) compared with males (21.1 %), and the fat patterning significantly differed at all eight body sites. The highest ratio between females and males was found at the lateral thigh (LT: 21.4/3.9 = 5.5) in all groups studied. Comparing D_{I} values of female and male athletes of the same sport, the highest ratios of the median D_{I} were found in Kenyan long-distance runners (57.6/8.6 mm = 6.7), followed by badminton players (73.8/21.9 mm = 3.4). Comparisons between SFs and US were analysed in the group elite judokas. Enormous differences of SAT between SFs and US technique were measured between two exemplarily chosen judokas with almost the same SF sum of eight body sites (44.9 mm vs 45.4 mm), whereby the D_{I} differed by a factor of four (20.0 mm vs 5.1 mm). In elite judokas, both measures for relative body weight, in terms of BMI and MI_1, were not correlated with D_{I}. In the females’ weight categories WC 48 or less to 70 kg or less (on the day of the official weigh-in before the competition), no significant correlation between the weight category and D_{I} were detected ($r_s = 0.107$, $p = 0.769$). Both measures for relative body weight (BMI and MI_1) were within a narrow range in Kenyan long-distance runners (females: BMI 16.8 - 19.5, MI_1: 17.3 - 20.7; males: BMI 16.1 - 20.7, MI_1: 17.6 - 22.0 kg m^{-2}, respectively). However, SAT thickness sums D_{I} strongly deviated in this group of athletes (females: 20-82 mm; males: 3-36 mm). Nineteen males out of 25 had D_{I} values below 15 mm.

Conclusion:

The recently standardised US method for measuring SAT thicknesses is applicable in field or lab settings and is cabable of detecting both SAT thicknesses with the embedded fibrous structures (fasciae) included or excluded on the high level of sensitivity necessary for monitoring the body composition of elite athletes. In the group of elite judokas, SF and US measurements were compared: the correlation results were poor. The relative body weights (BMI and MI_1) were within a narrow range in both Kenyan female and male long-distance runners, but variations in D_{I} were large. The standardised US method enables measurements of SAT with high accuracy and reliability and thus to determine the impact of body composition on performance with the high sensitivity necessary in elite athletes. For the field of sports medicine, accurate measurements of body composition are essential for raising the alarm when low weight and body composition disturbances appear.

Keywords: subcutaneous adipose tissue, body composition, sex differences, relative body weight, elite athletes, Kenyan runners, ultrasound

1 Introduction

Body weight and body fat are crucial performance factors in many sports (1, 2). The professional teams behind athletes are interested in monitoring small changes of body fat and muscle mass to manage dietary, exercise, or rehabilitation interventions. Extremely low-fat values or low body weight are often sought after in order to achieve performance advantages. Especially in weight-sensitive sports, including gravitational sports, weight class sports, and aesthetically judged sports (2). The dangerous disadvantages of restrictive eating in combination with compulsive exercise/or eating in high performance athletes should not be ignored (3). The Medical Commission of the International Olympic Committee (IOC) has been concerned about extreme weight loss strategies in elite athletes; in 2009, the Working Group on Body Composition, Health and Performance was set up to identify possible medical problems due to extreme weight reduction in weight-sensitive sports. The scientific work of this group includes the identification of research needs (2, 4, 5), the development of solution strategies (1), and contributions to the development of a novel ultrasound (US) method for measuring subcutaneous adipose tissue (SAT) thicknesses (6-8). This standardised US method reaches an accuracy (8) and reliability (9, 10) not achieved by previous methods.

1.1 Body Composition (BC) Research Areas and Measurement Methods.

Wang, Pierson, and Heymsfield (11) devided the field of BC into three areas (Figure 1) that are briefly described below.

Interconnecting Areas of BC Research:

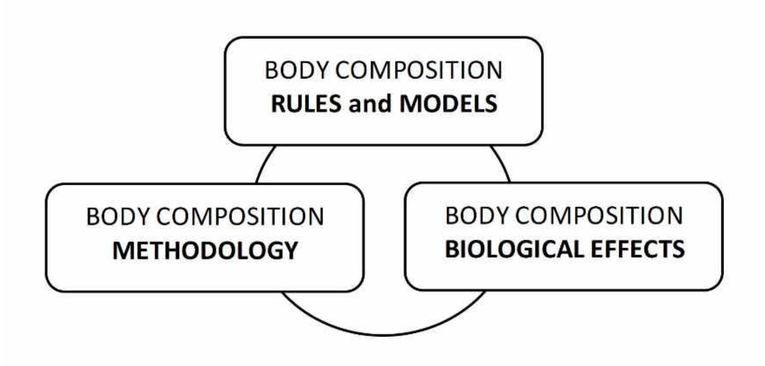


Figure 1: Three Interconnecting Areas of BC Research.

Modified from Wang ZM et al., 1992, "The five-level model: a new approach to organizing body-composition research," American Journal of Clinical Nutrition 56: 19–28 . Permission by the American Journal of Clinical Nutrition. © Am J Clin Nutr. American Society for Clinical Nutrition.

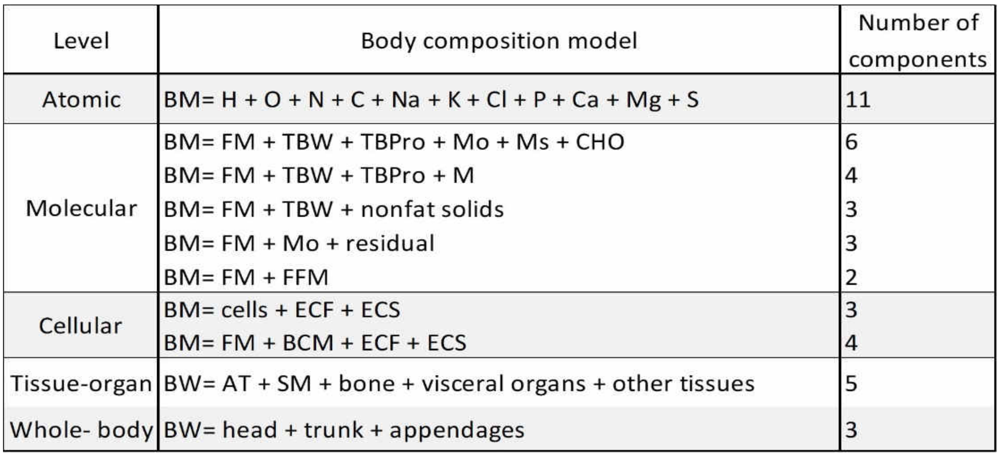
Body Composition Rules and Models

The area relates to BC rules and models with five levels of increasing complexity (11):

I.	Atomic Level	Chemical
II.	Molecular Level	
III.	Cellular Level	Anatomical
IV.	Tissue-System Level	
V.	Whole Body Level	

These models are widely accepted for BC studies (12). The sum of all atoms, molecules, cells, tissues, and organs at each level is equivalent to an individual's body mass (*m*) (Table 1:).

Table 1: Body Composition Levels and Numbers of Measurable Components.



Level	Body composition model	Number of components
Atomic	BM= H + O + N + C + Na + K + Cl + P + Ca + Mg + S	11
Molecular	BM= FM + TBW + TBPro + Mo + Ms + CHO BM= FM + TBW + TBPro + M BM= FM + TBW + nonfat solids BM= FM + Mo + residual BM= FM + FFM	6 4 3 3 2
Cellular	BM= cells + ECF + ECS BM= FM + BCM + ECF + ECS	3 4
Tissue-organ	BW= AT + SM + bone + visceral organs + other tissues	5
Whole- body	BW= head + trunk + appendages	3

(AT) adipose tissue, (BCM) body cell mass, (BM) body mass, (CHO) carbohydrates, (ECF) extracellular fluid, (ECS) extracellular solids, (FFM) fat-free mass, (FM) fat mass, (M) mineral, (Mo) bone mineral, (Ms) soft tissue mineral, (SM) skeletal muscle, (TBPro) total body protein, (TBW) total body water. Atomic: (H) Hydrogen, (O) Oxygen, (N) Nitrogen, (C) Carbon, (Na) Sodium, (K) Potassium, (Cl) Chlorine, (P) Phosphorus, (Ca) Calcium, (Mg) Magnesium, (S) Sulphur.
Adapted with permission from: Shen W, 2005, p. 11 "Representative Multicomponent Models at the Five Body Composition Levels", in Heymsfield SB et al. Human Body Composition. © Human Kinetics, Inc.

The five-level models describe different components into distinct levels, but components at higher BC levels are also included in lower levels. Heymsfield, Wang, Baumgartner, and Ross described in their review: *"A classic example is that adipose tissue, a tissue-system level component, includes components such as adipocytes at the cellular level, lipids at the molecular level, and carbon at the atomic level"(13).*

Level I – Atomic Level

The human body consists 50 of the 106 elements. Their distribution in organs and tissues has been extensively described (14). About 98 % of *m* are: oxygen (>60 %), carbon (23 %), hydrogen (10 %), nitrogen (2.5 %), calcium, and phosphorus, and the remaining ~2 % are further 44 elements (14).

Table 2: Atomic Level of Body Composition and Possible Measurement Methods.

LEVEL	METHODS (in vivo)	PRIMARY MEASUREMENTS
ATOMIC	Whole body counting of ^{40}K (TBC) IVNAA X-ray fluorescence analysis	Total body potassium N, H, Ca, Cl, Na, P trace elements: lead, cadmium, mercury, iodine

Abbreviations: (TBK) total body potassium, (IVNAA) in vivo neutron activation analysis, (N) Nitrogen, (H) Hydrogen, (Ca) Calcium, (Cl) Chlorine, (K) Potassium, (Na) Sodium, (P) Phosphorus. Cited from (11) and (15).

Level II – Molecular Level

According to Wang et al. (11), the six major components related to the 70 kg Reference Man (14) are water (60 %), separated into 26 % extracellular, and 34 % intracellular compartments, whereas the extracellular water compartment can be separated into sub-compartments: interstitial, plasma, connective tissue, bone, and gastrointestinal tract (13), lipid (17 % nonessential (fat), 2.1 % essential), protein (15 %), minerals (5.3 %), and carbohydrates (~ 400 g) not included in the Reference Man. Shen, St-Onge, Wang, and Heymsfield (16) draw attention to the fact that many different definitions have been used at this level of BC: *"The term lipid and fat may be used interchangeably, but their meanings in the body composition research field differ"* (16). Therefore, these authors used the term "lipid" only for ether and chloroform extractable lipids in human tissues and the term "fat" for contained triglycerides. In humans, approximately 50 different lipids (e.g., triglycerides, phospholipids) are known (11). Therefore, the term "fat" is just a subcategory of lipids. This information may be of importance when constructing BC models or when interpreting data of different BC methods. An example by Heymsfield, Wang, Baumgartner, and Ross (13) is that: *"adipose tissue, a tissue-system level component, includes components such as adipocytes at the cellular level, lipids at the molecular level, and carbon at the atomic level. Loss or gain of adipose tissue with a new intervention reflechts changes in corresponding components at the cellular, molecular, and atomic levels"*.

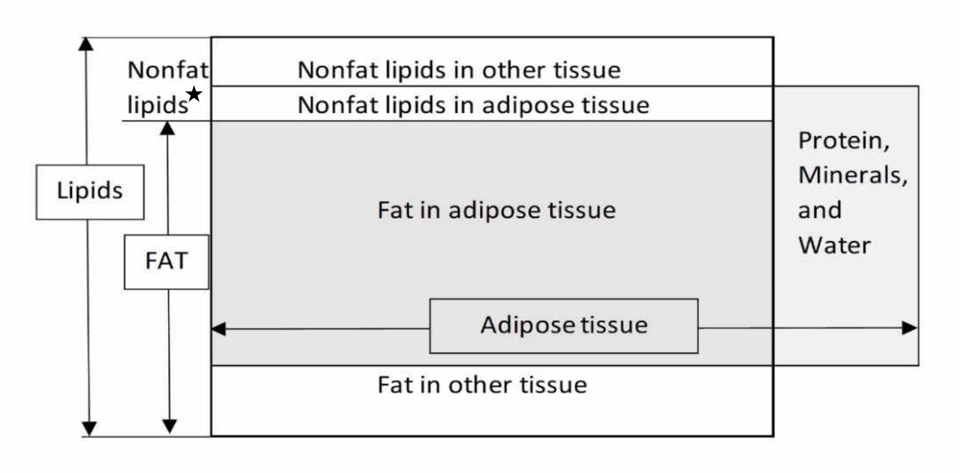


Figure 2: Relationship of Lipids (at Molecular Level) and Fat (Tissue-System Level).

(★) non-fat lipids include phospholipids, sphingolipids, and steroids.
Adapted with permission from: Shen W., 2005, p. 11 "Representative Multicomponent Models at the Five Body Composition Levels", in Heymsfield SB, et al. Human Body Composition. © Human Kinetics, Inc.

From a physiological point of view, lipids can be classified into essential and nonessential lipids, in which sphingomyelin and phospholipids are essential lipids and serve important functions (11). Nonessential lipids, mostly in the form of triglyceride, provide thermal insulation and energy storage. The Reference Man consists of 17 % lipids. About 10 % of total lipids are reported as essential and 90 % as nonessential (11, 14).

Protein

About 11 % of proteins were measured in the reference man (14). Non-invasive BC methods may not differentiate among all the different proteins in humans. However, the estimation of total protein and muscle and non-muscle protein may be estimated in vivo (13).

Bone Minerals

About 5 % of body mass in adult humans are minerals subdivided into two components: bone minerals (BM) (osseous) and non-bone (soft-tissue minerals, extraosseous) minerals. The main constituent (>99 %) of BM is calcium hydroxyapatite.

Carbohydrates

Healthy adults contain less than 1 kg of glycogen. The liver and skeletal muscle are the main pool for intracellular glycogen (13).

The molecular level (Level II) of BC is fundamental to BC research. At present, the most accurate method for the estimation of body fat (BF) is multi-component models (2).

Table 3: Molecular Level of Body Composition and Possible Measurement Methods.

LEVEL	METHODS (in vivo)	PRIMARY MEASUREMENTS
MOLECULAR	DXA Isotope dilution technique NAA Total body densitometry (UWW, ADP)	Total body mineral (TBM) Total body water (TBW) Protein – estimated indirectly by measuring (TBN) at atomic level with assumptions: 1. All TBN is contained in Pro, and 2. 16% of Pro is N. Total BF (assumed density of fat = 0.90 g/cm^3 and of FFM = 1.1 g/cm^3)

Abbreviations: (NAA) neutron activation analysis, (TBN) total body nitrogen, (UWW) under water weighing, (Pro) Protein, (ADP) Air-displacement plethysmography, (FFM) fat-free mass, (BF) body fat. Cited from (17).

Level III – Cellular Level

The next higher level is the cellular level, where different components at the molecular level are assembled into cells that create the living organism (11). The cellular level includes three components: extracellular solids, extracellular fluids, and cells. Within the cells further components can be subdivided: fat and body cell mass (15, 16). According to Wang et al. (11) cells vary…*"in size, shape, elemental and molecular composition, metabolism, and distribution.*

Extracellular solids (ECS): collagen, reticular, and elastic fibres, and *Extracellular fluids (ECF):* distributed into plasma in the intravascular space and interstitial fluid in the extravascular space (11). The Reference Man (14) consists of ~5 % plasma and interstitial fluid (about 20 % of *m*). A widely used equation at the cellular level is

$$\boxed{m = \text{fat cells} + \text{BCM} + \text{ECF} + \text{ECS}\ (11).}$$

Heymsfield et al. (13) describes the following: *"There a many relatively stable cellular-level relationships that are used in body composition research, and some of the more important of these are as follows: K/intracellular water = 159 mmol of K/kg of* H_20 *= 6.22 g of K/kg of* H_20*; K/body cell mass = 4.69 g/kg; Ca/extracellular solids = 0.177 kg/kg; and extracellular water/extracellular fluid = 0.92".* (13)

Bea, Cureton, Lee, and Milliken mentioned (17) that it is not possible to measure every single cell. According to this authors researchers have grouped cells into: (a) connective cells (adipocytes, blood cells, and bone cells), (b) muscular cells (striated skeletal, smooth, and cardiac cells), (c) nervous cells, and (d) epithelial cells (17).

Table 4: Cellular Level of Body Composition and Possible Measurement Methods.

LEVEL	METHODS (indirect, estimated)	PRIMARY MEASUREMENTS (estimated)
CELLULAR	0.00833 x TBK TBCa/0.177 (through NAA) Dilution techniques	BCM ECS Plasma volume, and interstitial fluid content of ECF

Abbreviations: (BCM) body cell mass, (TBK) total body potassium, (ECS) extracellular solids, (ECF) extracellular fluids, (TBCa) total body calcium. Cited from (17).

Level IV - Tissue-Organ Level

The fourth level of BC research is known as the tissue-organ level. Cells at the cellular level are built up into tissues or organs for the next higher organisational level. The main components at this level are skeletal muscles, visceral organs, bones, adipose tissue, and other organs (brain, heart, liver, and spleen) (16). All included organs and tissues are metabolically active (12).

Tissues: All tissues contain cells and can be grouped into four categories: muscular, connective, epithelial, and nervous tissues (11). According to Wang et al. (11), *m* is defined as follows:

$$\boxed{m = \text{muscular tissue} + \text{connective tissue} + \text{epithelial tissue} + \text{nervous tissue}}$$

The sum of bone, adipose tissue, and muscular tissue is about 75 % of the Reference Man (11, 14). Bone, as one part of connective tissue, contains mainly hydroxyapatite, and small amounts of calcium carbonate (11). Adipose tissue, another type of connective tissue, is made up of adipocytes (fat cells), including collagenous and elastic fibres, fibroblasts, and capillaries. According to its distribution, adipose tissue can be subcategorised into subcutaneous, intraabdominal (visceral – deep abdominal, or intraperitoneal adipose tissue), interstitial, and yellow marrow (11, 18, 19). Subcutaneous adipose tissue (SAT) makes up about 80 % of total body fat (TBF) (18, 20).

Organs: Some organs can be single solid substance such as brain, heart, liver, and spleen, or dispersed throughout the whole body, e.g. skin and skeletal muscle (16).

Systems: Many organs are connected to systems (e.g., digestive: esophagus, stomach, intestine, liver, pancreas etc.). Every single organ again contains different tissues such as muscular, connective, epithelial, and nervous tissue, and each tissue arises from many cells and extracellular material from lower BC levels (11). The *m* of humans including the main systems can be estimated as follows: According to Wang et al. (11):

$$\boxed{\begin{array}{c} m = \text{musculoskeletal} + \text{skin} + \text{nervous} + \text{circulatory} + \text{respiratory} + \text{digestive} + \\ \text{urinary} + \text{endocrine} + \text{reproductive systems} \end{array}}$$

According to Wang et al. (11), the following equation for *m* can be used:

$$\boxed{m = \underbrace{\text{adipose tissue} + \text{skeletal muscle} + \text{bone} + \text{viscera} + \text{blood}}_{85\ \%} + \underbrace{\text{residual}}_{15\ \%}}$$

Table 5: Tissue-System Level of Body Composition and Possible Measurement Methods.

LEVEL	METHODS (in vivo)	PRIMARY MEASUREMENTS
Tissue-System	CT	Volume of SAT, VAT, visceral organ volumes, skeletal muscle mass
	Multi-slice CT	Whole-body AT volumes
	MRI	Major tissue system-level components
	(TBK) 24 h urinary creatinine excretion	Skeletal muscle mass
	NAA	Nitrogen content
	DXA	Bone tissue
	Ultrasound	SAT

Abbreviations: (CT) computerized axial tomography, (SAT) subcutaneous adipose tissue, (VAT) visceral adipose tissue, (AT) adipose tissue, (TSL) tissue-system level, (MRI) magnetic resonance imaging, (TBK) total body potassium, (DXA) dual-energy X-ray absorptiometry, (NAA) neutron-activation analysis. Taken from (8, 11, 16, 21, 22).

Level V – Whole Body Level

The whole body level as the fifth and highest level of BC studies is characterised by more than ten body categories (11) which include stature (general body size), segment lengths, body breaths, circumferences (e.g. upper arm, waist, hip, and thigh), skinfold thicknesses, body surface area, body volume, body mass, and body density (11). Many widely used variables at this level are described by anthropometric measurements (16, 21, 23).

Table 6: Whole Body Level of Body Composition and Possible Measurement Methods.

LEVEL	METHODS (in vivo)	PRIMARY MEASUREMENTS
Whole body	Anthropometry: external characteristics (24).	Physical assessment of body size, shape, and composition. Indices include BMI, MI_1, W, L.
	UWW, Bod Pod (25)	Body volume, BF, and FFM

	3D scanning (laser, light, or infrared technologies (26))	For determining body volume, surface area, segment lengths, and girths
	Skinfolds; ISAK protocol (27)	Sum of skinfolds, or single sites
	Ultrasound; IASMS -standardised protocol (8)	SAT thicknesses, SAT patterning, TSAT

Abbreviations: (BMI) body mass index; BMI $= \frac{m}{h^2}$), (MI$_1$) mass index; MI$_1 = 0.53\frac{m}{hs}$, (s) sitting height, (m) body mass, (h) stature, (W) waist-to-height ratio, (L) leg-to-height ratio, (SAT) subcutaneous adipose tissue, (UWW) under water weighing, (Bod Pod) air displacement plethysmography, (FFM) fat-free mass, (TSAT) total subcutaneous adipose tissue, (ISAK) International Society for the Advancement of Kinanthropometry (IASMS) International Association for Sciences in Medicine and Sports. Sited from (2, 8, 17, 24-26, 28).

1.1.1 Molecular and Anatomical Approaches in Multicomponent Models

Over the last seven decades, the most frequently used method to define the human body at the molecular level has been the two-component (2-C) model, based on hydrodensitometry (29). According to Wang, Shen, Withers, Steven and Heymsfield (29), two models (the body mass model, and the body volume model) can be determined. The latter is based on two assumptions: fat mass (FM) and fat-free mass (FFM) densities are constant between and within participants (0.9007 g/cm^3 at 36° C, 1.100 g/cm^3 at 36° C, respectively). For estimating FM and FFM using the 2-C method (originally introduced by Behnke (30)), body weight (m in kg) is measured with a scale, and body volume (BV, in litres) is measured by underwater weighing (UWW) or at present frequently by air displacement plethysmography (ADP) (29, 31). To reduce possible errors of the simplified 2-C models (e.g., assumptions that densities of FFM are constant), multicomponent models were developed.

Three-Component (3-C) Model

This model divides the human body mass (m) into three components. In addition to the two components, namely FM and FFM, the latter were (originally developed by Siri (32)) further divided into water and residual. The total body water content (TBW) using the tritium- or deuterium-labelled water dilution technique is extensively described elsewhere (31) and briefly introduced later.

Four-Component (4-C) Model

The four-component model (4-C), as a widely used approach for different research questions, divides FFM into further components: water, protein, and mineral (15). According to Ackland, Lohman, Sundgot-Borgen, Maughan, Meyer, Stewart, and Müller (2), the equation for estimating FM is as follows:

$$\boxed{FM = C_1\ BV - C_2\ TBW + C_3\ M - C_4\ BM\ (2).}$$

Abbreviations: (BV) body volume, (TBW) total body water, (M) bone mineral, (BM) body mass.

Another formula used to estimate FM was introduced by Withers, Smith, Chatterton, Schultz, and Gaffney (33), and applied for research questions working with highly trained athletes (34):

$$\boxed{FM = 2.513 \text{ x } BV - 0.739 \text{ x } TBW + 0.947 \text{ x } Mo - 1.790 \text{ x } BM\ (33).}$$

Wang, Pi-Sunyer, Kotler, Wielopolski, Withers, Rierson Jr, and Heymsfield (35) improved traditionally used models of Brožek, (36), and Selinger (37) for estimating soft tissue minerals (Ms) as follows:

$$\boxed{Ms\ (kg) = 0.0129 \text{ x } TBW\ (35).}$$

The 4-C model is described as follows:

$$\boxed{FM\ (kg) = 2.748 \text{ x } BV - 0.699 \text{ x } TBW + 1.129 \text{ x } Mo - 2.051 \text{ x } BM\ (35).}$$

This improved formula for assessing BF (4-C model) at the molecular level is well accepted in the literature (38), and is often used as a criterion method when compared with other techniques.

Multicomponent Model

Several multicomponent models have been published (differing in methodologies) and are used to examine complex research questions (39). When using models with five, six or more components, human body mass is divided into water, protein, glycogen, osseous bone mineral, non-osseous bone mineral, and fat (17). The most commonly used multicomponent model (laboratory techniques) according to Rolland (39) is total body mass divided into FFM and FM (by UWW or ADP), where FFM is further separated into bone minerals (by DXA), water (by isotope dilution), and fat-free soft tissue (by subtraction). The 4-C component model is immensely popular and is often used as a criterion method for BC evaluation or validation studies (2, 29, 38, 39). Multi-component models have different methodologies, and therefore different procedures can be found (Table 7 and reference (39)).

Table 7: Multicomponent Model and Possible Measurement Methods.

Component	Method
Total body nitrogen, Calcium, chloride, sodium, carbon	NAA

Total body potassium	TBP (^{40}K)
Total body water	Dilution techniques

Abbreviations: (NAA) neutron activation analysis, (TBP ^{40}K) total body potassium-40 counting. Cited from (17).

To summarise, Wang et al. (11) introduced five different levels of body composition (Table 1). Each of these levels divides the human body into further components. The human body consists of about 50 elements, different molecules, body cells with varying sizes and functions, several tissues, organs, and systems. When focusing on the molecular-level components, the human body is mainly composed of water, fat, proteins, and minerals (40). The best choice of measurement technique greatly depends on the individual research question. BC measurement methods vary in practicability, availability, complexity, and precision. For sport scientists, nutritionists, and coaches working with highly trained athletes, it is important that BC results are interpretable, and capable of visualizing small changes of BC. Therefore, at this point of the thesis, widely used BC measurement techniques, especially as applied to elite athletes, are described. Additionally, possible biological and/or technical limitations of cited techniques will also be described.

1.2 Techniques for the Assessment of Body Composition in Athletes

All BC measurement techniques, to some extent, struggle with errors, either technical (precision, reliability, and objectivity) or biological (accuracy, and validity) (2, 41, 42). Before reviewing possible laboratory and field BC measurement techniques, a short summary of important key terms used in BC research are given here.

1.2.1 Important Variables for Assessing Minimal Measurement Error

Minimal Measurement Error (Reliability, Precision, Accuracy)

According to Atkinson and Nevill (43), "*minimal measurement error (reliability) during the collection of interval- and ratio-type data is critically important to sports medicine research. The main components of measurement error are systematic bias (e.g. general learning or fatigue effects on the tests) and random error due to biological or mechanical variation*". For describing "absolute reliability" the authors suggest that the standard error of measurement (SEM; the smaller, the more reliable), coefficient of variation (CV), and limits of agreement (LOA) should be used (43). Further, these authors stated that by using these variables (SEM, CV, and LOA), the "real" change between individual athletes and repeated measurements can be predicted sufficiently.

Another commonly used term in BC research is precision, also called reproducibility or repeatability. Precise results mean that low variability is given in comparative measures. If a method achieves two similar BC values, this does not implicitly mean that this measurement technique is sufficiently accurate. Lohman, Milliken, and Sardinha (41) explained: "*The use of reliability instead of precision values has the advantage that the measure has no units; it is therefore possible to compare the precision of variables with different units*". The intra-class correlation coefficient (ICC) (ranging from 0 to 1, where 1 is exceptionally reliable) is the most commonly used reliability measure. For the collection of data of athlete groups with varying physiques (e.g. lean, high muscle mass, underweight, tall or small) it is important to reduce possible errors by choosing a method where the procedure has been standardized (2, 4, 8, 9, 44).

1.2.2 Commonly used Body Composition Assessment Methods Applied in Athletes:

Athletes' physique is an important performance factor when competing at highest level. At some points during an athlete's career (e.g. return to sport after injuries, weight cutting in combat sports, gain of muscle mass), athletes deliberately change their physique to compete with performance advantages (1, 2, 4, 8, 42). As mentioned above, many athletes (especially in weight-sensitive sports) reduce BF and body weight with extreme methods. The IOC working group recognised that further scientific research is urgently needed to "protect" competitive athletes from possible long-term health consequences. A recently published manuscript written by Ackland, Lohman, Sundgot-Borgen, Maughan, Meyer, Stewart, and Müller (2) describes the current status of BC assessment in sport. In another manuscript, this group of experts assessed the current use of BC assessment methodologies in different labs around the world (4). According to these authors, the most used BC techniques (up until 2013) applied in athletes were skinfolds (SFs) (Σ 7-8 sites) using the International Society for the Advancement of Kinanthropometry (ISAK) protocol (>50 % of respondents of 188 participants in different labs from 33 countries), followed by SFs using a formula for estimating percent fat ("conventional" skinfold approaches), DXA (~38 %), Bioelectrical Impedance (~30 %), and more than 10 % of respondents used other techniques like magnetic resonance imaging (MRI), computed tomography (CT), three-dimensional laser body scanner (3D scanner), lipometer, a 4-C model including DXA, Bod Pod, deuterium dilution for total body water and fat-free mass estimation, somatotype, five-way fractionation model and proportionality. At that point, the use of ultrasound (US) was only reported in Europe (4).

The most frequently used methods applied in athletes up until 2013 (4) are listed below, including possible advantages and disadvantages of the listed methods.

- *Surface Anthropometry:* Skinfolds, as one of the most used methods for assessing adipose tissue in athletes, measure adipose tissue (generally from eight body sites when following the ISAK protocol) on the anatomical level using measurements of a double layer of skin and subcutaneous fat together in a compressed state (7, 24, 45). In recent years more than 100 different prediction equations and formulas have been developed with percentage fat as the most used variable (2, 46). Marfell-Jones, Nevill, and Stewart stated (46): *"Researchers should be wary, however, of such predictions, given that, for intersubject comparisons, their accuracy relies on the validity of five assumptions in making the translation from the linear distance across a skinfold to percentage fat".* When reporting percentages of body fat (%BF) using skinfolds (SFs) it should be considered that inconstant compressibility of skin and underlying adipose tissue lowers validity. Compressibility of SAT differs by about 25 % and 37 % depending on the site (47) and among individuals (7); moreover skin thickness varies between different sites (48) and significantly between females and males (49). Therefore, no constant compressibility can be assumed. For achieving accurate total body fat (BF) results using SFs, fat patterning, and the ratio of external (subcutaneous) to internal (e.g. intra-abdominal, or ectopic fat) fat needs to be constant (46). Instead of using %BF, with various assumptions, ISAK nowadays supports to report SF thickness sums and fat patterning when monitoring athletes over time. Despite its known weaknesses (SEE: 3 % to 4 % (50), SEE: 2.5 % to 3 % (51), SEE: of about 5 % (2)), SFs are still very popular. To date, this quick, cheap, and effective way to monitor fat patterning in the lab or in the field has led many observers to overlook this method's possible weaknesses. For best practice, the International Society for the Advancement of Kinanthropometry (ISAK) has standardised landmarking and measuring procedures and provided international standards for surface anthropometric assessments, including skinfolds, circumferences, lengths, and bone breadths measurements (24). Prior to 1988, there was no standardised protocol, and therefore participants were measured without one. An appropriately trained measurer following ISAK guidelines (two measurements should be within 5 % deviation) can obtain usable results given the fact that fat and skin differ in compressibility, and therefore, the validity may not be improved by the measurer.

- *Anthropometry*: Anthropometric measurements are commonly used to assess the size, shape, and composition of the human body. To date, anthropometric measurements are divided into two categories, BC and body size. BC identifies the relative percentages of fat mass and fat-free mass (2-C model). Anthropometric measurements are immensely popular for monitoring the BC of individual athletes before and after specific periods of training, or for comparing groups of athletes, for further health screenings (e.g. waist-to-hip ratio, waist-to-height ratio, relative body weight), or monitoring of growth in children and adolescents (52). Additionally, anthropometric prediction equations are used to estimate %BF, or FFM from body mass, standing height, skeletal diameters, and circumferences. According to Meyer (4) anthropometric measurements are chosen among various BC methods in use due to its simple, quick and cost-effective laboratory implementation. The relative body weights in terms of the body mass index (Quetelet's index) $BMI = \frac{m}{h^2}$ (m: body mass, h: stature) and the improved mass index MI_1 (increasingly recommended (1, 22) $MI_1 = 0.53\, m/(hs)$) are widely accepted as measures of relative body weight, but not accepted for BF analyses, especially in elite athletes (1, 2, 22). Recently, Gallagher, Heymsfield, Heo, Jebb, Murgatroyd, and Sakamoto (53) developed %BF prediction equations based on the BMI. The aim of their study was to report possible differences in fatness classified by age, sex, and ethnicity. BF was measured by DXA or a 4-C model in subjects from three ethnic groups. The authors found that Asians (≤ 59 years) had slightly higher values of %BF for any given BMI. The prediction formulas were used to create provisional healthy %BF ranges for the published BMI classifications for underweight, overweight, and obesity (53). It has to be pointed out that such reductionistic approaches like BMI for determining body fat may show correlations for groups of untrained persons, but are not useful for determining body fat of individuals. Bodily hard working persons or athletes may have BMI values above 25 or even above 30 kg m^{-2}, but very low fat.

Table 8: The classification of the body mass index (BMI) by the World Health Organization for adults independent of sex.

Classification		Body mass index (kg m^{-2})
Underweight	Severely underweight	<16.00
	Moderately underweight	16.00–16.99

	Mildly underweight	17.00–18.49
Normal range		18.50–24.99
Overweight	Pre-obese	25.00–29.99
	Obese class I	30.00–34.99
	Obese class II	35.00–39.99
	Obese class III	≥40.00

Cited from World Health Organization (WHO), 1995 (52, 54).

The BMI is often cited as being highly correlated with other health indicators, but according to Ackland and colleagues (2): …*“that demonstration of a strong association at the population level is not the same as a technique providing accurate, precise and reliable body composition data for an individual”.*

The WHO Expert Committee on Physical Status has already pointed out the weaknesses of the BMI in 1995, and stated the following: *“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”* (55). Recently a new measure for estimating the ‘relative body mass’ has been introduced (2, 56, 57), and has already been applied for different studies of athletes and non-athletes (8, 9, 22, 28, 58, 59). The MI$_1$ considers the individual’s leg length l (by measuring sitting height s to determine the Cormic index $C = \frac{s}{h}$). The derivation of the MI$_1$ formula is explained elsewhere (22). According to Sundgot-Borgen, Meyer, Lohman, Ackland, Maughan, Stewart, and Müller (1), relative body mass (MI$_1$) may be an important criterion for ‘raising the alarm’ and leading to a ‘no start’ decision before competition, and therefore is of relevance when assessing elite athletes.

Various measurements and indices are used when assessing an athlete’s physique (e.g., waist-to-hip ratio, waist-to-height ratio, body roundness index (BRI) $BRI = 364.2 - 365.5 \cdot eccentricity$; $eccentricity = (\sqrt{a^2 - waist\ circumference^2})/a$, body adiposity index (BAI) $(BAI = \left(\frac{hip\ circumference}{stature^{1.5)}}\right) - 18)$, and body shape index $(ABSI) = waist\ circumference/(BMI^{\frac{2}{3}} \cdot stature^{\frac{1}{2}})$) (60). These novel indices have recently been used to predict adiposity in 209 female and male athletes to analyse the association between these body indices and adiposity as assessed by a 4-C model

(60). The researchers of this study concluded that none of the indices (BMI, BAI, ABSI, and BRI) are recommended to predict adiposity in athletes, and that these indices should not be used to replace other BC field methods (60).

Regardless of the method used, it is highly recommended to follow a standardised protocol (e.g., ISAK (27)) for measuring circumferences, stature, and body mass because different procedures may impact the results. As an example, protocol variations of arm position while measuring the waist girth influences the magnitude of the waist girth (61). Lennie, Amofa-Diatuo, Nevill, and Stewart (61) measured the waist girth in 92 adults with arms relaxed, abducted, horizontal, folded across the chest (three variations), and raised vertically. The greatest error was shown with arms raised vertically, the lowest error using the ISAK protocol (arms folded across the thorax). Therefore, following a protocol (e.g., arm position, food, fluid intake, and breathing control) is highly recommended when measuring waist girth in humans, especially in clinical and public health settings.

Surface Anthropometry for Talent Identification and Development.

Body size, athlete's shape, and composition has an influence on performance (42). Therefore, measuring anthropometric variables in adolescents has also been recognised as useful to identify potential talents for certain sports, and to monitor talent development to achieve full potential within the chosen sport (62). According to Slater, O´Connor, and Kerr (63), the specific physique characteristics associated with competitive success vary from sport to sport. As an example, taller athletes are more successful in basketball, netball, and volleyball, as excess adipose tissue ('ballast mass') will negatively affect performance in several sports (62). Anthropometric and physique traits do have a role as part of a talent identification process but should not be overemphasised, in order to avoid the early pressure to reduce BF and body weight in an unhealthy way in youth athletes. Hume, and Stewart (62) stated: *"… an athlete's physique responds to the periodisation in a training* programme *in a dynamic way, by adjusting adipose tissue, muscle tissue, glycogen stores and water balance"*. These have important implications (e.g., for trainers) especially in weight class sports, where athletes may reduce body weight frequently to compete in a given weight category.

- *Bioelectrical Impedance Analysis* (BIA): This commercially available method is often used due to portability, availability, cost-effectiveness, and simplicity, and the operator does not require extensive training (15, 64). Measurements typically are performed by using four electrodes placed at the wrist and at the ankle (positioning varies according to manufacturer) (31). After correct electrode positioning, the participant lies in supine position. Further information about the athlete preparation procedure for BIA assessment may be found elsewhere (64). For estimating FFM, FM, and TBW, a weak alternating current (low frequencies considered to be < 50 kHz, and higher frequencies > 50 kHz (65)) is sent through the body to calculate the body`s impedance (*R* and X_C) (65). The principle of BIA is that the impedance to a flow of an electric current (typically at 50 kHz) from electrodes is inversely proportional to the total body mass (31, 66). To estimate body compartments, many assumptions have to be made. According to Norgan: *"The theory is that the body is a simple cylinder of known length and cross-sectional area, that water and electrolytes are uniformly distributed and that body temperature is constant"*(66). These assumptions lead to measurement errors, which need to be considered when assessing high performance athletes. The European Society for Clinical Nutrition and Metabolism (ESPEN) has published guidelines for the use of BIA. In part I, Kyle, Bosaeus, De Lorenzo, Deurenberg, Elia, Gomez et al. (67) reviewed BIA equations published since 1990 for FFM, FM,TBW, extracellular water (ECW), and intracellular water (ICW). The reported SEE for %FM (≥3.8 %) indicates poor accuracy using BIA as the chosen BC measurement technique (67). In part II, Kyle, Bosaeus, De Lorenzo et al. (68) reported that the BIA results are strongly affected by whether participants were measured in a fasted or non-fasted state. Further, exercise decreased *R* by approximately 3 % and X_C by 8 %, which should be mentioned when assessing athletes. Moon stated: *"Prediction equations developed or validated in athletes using a criterion method that does not use a multiple-compartment model with a TBW estimation may not be appropriate for use in any athletic population"* (65). In conclusion, frequent hydration changes (e.g., 'weight cutting' in combat sports) while training sessions, or fluid and food intake may reduce the validity of this method.

- Hydrodensitometry or Underwater Weighing (UWW): was pioneered by Behnke and colleagues in 1942 (69). The authors investigated the values of specific gravity of 99 adult men. The measurement of body volume (BV), based on Archimedes' principle, is determined by hydrostatic weighing. All subjects were completely submerged in water. The body mass was weighted two times for accuracy reasons, one after maximum inspiration, and a second time after maximum expiration. The BV is equal to weight loss in water, divided by the density of water ($BV = (W_a - W_W)/D_W$) (70). Different equations for the calculation of %BF based on body density have been introduced (36, 71). The greatest error when measuring the specific gravity according to Behnke, Feen, and Welham (69) arises from *"…the determination of residual lung volume. If the variation in this measurement is of the order of 200 cc., values for specific gravity will be subject to an error of ± 0.003"*. The reliability of UWW in the study from Friedl, DeLuca, Marchitelli, and Vogel was no better than ± 1.0 % for BF or ± 0.002 g/cm^3 (72). Large technical errors for repeated body density evaluations (0.0030 g/mL) or BF determinations from UWW in men (1.1 %) and women (1.2 %) should be considered when using this measurement procedure in practice (73). Technical error (TE) scores for UWW according to Clasey, Kanaley, Wideman, Heymsfield, Teates, Gutgesell, Thorner, Hartman, and Weltman (74) ranged from ± 5.17 to ± 6.39 %BF, whereas 95 % CIs represented with the Bland–Altman analyses ranged from ± 5.1 to ± 12.0 % BF. UWW is not accurate enough for detecting small changes of %BF or FFM when measuring highly trained athletes after set training interventions (75).

- Air Displacement Plethysmography (ADP): The Bod Pod®, Body Composition System, as a widely used BC measurement tool uses the relation between pressure and volume to derive the total body volume of a participant (76) to further estimate fat mass and lean body mass in a wide range of individuals (2-C model, see 1.1.1). This BC measurement technique uses relevant gas laws, Boyle's law and Poisson's law, where the former states: …*"that a constant temperature (isothermal conditions), the product of pressure and volume is constant"* (76), and the latter *"describes the relationship between pressure and volume under adiabatic conditions as $P_1/P_2 = (V_2/V_1)^\gamma$ where γ is the ratio of the specific heat of the gas at constant pressure to that at constant volume"* (76). The full test procedure of the BOD Pod® System, which largely replaced the well-known densitometric method to estimate body volume, may be found elsewhere (25, 76). When performing repeated measurements on children, discrepancies in volume measurement (when BV < 40 L) occurred. Therefore, although this method is known as more practical in comparison to UWW, it is not recommended to use this approach in all population groups. When measuring BV using ADP compared to UWW, the precision (0.07 L and 0.11 L) of Bod Pod was better (70). Kerr, Slater, and Byrne (77) studied the impact of TBW, acute food and fluid intake and physical exercise in 2-C, 3-C, and 4-C BC models. When measuring participants under dehydrated conditions %BF may be underestimated

(1.1%), which can be not ignored when measuring longitudinal changes in %BF in elite athletes (77). Large errors of FM (653 g) were found when no standardised protocol has been followed; in addition, 500 g food and one litre of water presented measurement errors of 660 g FFM and 820 g FM in their study (77). Reliable assessments may be possible when the observer follows a standardised protocol as recommended for all BC measurement methods (25, 44).

- *Dual Energy X-Ray Absorptiometry (DXA):* DXA is an accepted reference technique for measuring bone mineral density (BMD) and bone mineral content (BMC) (78). Today after many years of development, modern DXA devices (GE Healthcare iDXA, Hologic Horizon DXA system) generate very detailed images with high contrast (79). The whole body can be scanned to measure total BMD (g cm $^{-2}$), regional BMD (e.g., left arm versus right arm), and bone mineral content (g). In the last decades, DXA has also been used to generate BC data (lean mass and FM) by emitting two different sources of X-ray energy (73, 78). Reports generate total and regional fat mass (g), lean mass plus bone mineral content (fat-free mass, g), total mass (g) (e.g., left arm), and percentages of fat. As an example, Hologic reports adipose indices i.e., total %BF, fat mass/height^2 (kg m^{-2}), android/gynoid ratio, %fat trunk/% fat legs, trunk/limb fat mass ratio, and lean indices, i.e., lean/height^2 (kg m^{-2}), and appendicular lean/height^2 (kg m^{-2}). In the last years, DXA has improved in table sizes; for example, the Norland Elite scanner may scan subjects of up to 283.5 kg body mass, 137 cm body breath, and 228 cm body height (versus smaller DXA systems (Figure 3) (80). The drawbacks of DXA should be mentioned, especially regarding measuring elite athletes. According to Shepherd, Ng, Sommer, and Heymsfield (80), DXA underestimates the mean fat mass (compared with a whole body CT) by 5 kg. In elite judokas DXA was compared with a four-compartment (4-C) reference model as the criterion method to monitor small changes of fat values from a period of weight stability to prior to a competition (38). These authors found that DXA overestimated %FM and FM changes at the lower ends and underestimated FM changes at the upper ends (individual error reached 6.3 kg of FM changes), which is very high when discussing performance strategies in elite athletes. The 95 % LOA (± 1.96 SD) for %FM ranged from -3.7 to 5.3, and for FM (kg) from -2.6 to 3.7 (38).

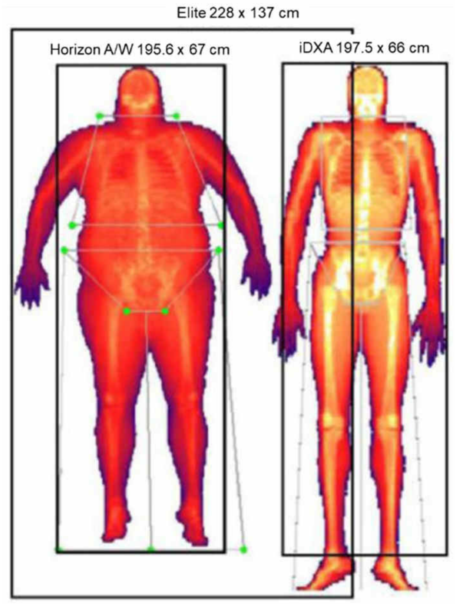


Figure 3: Different table scan areas of DXA systems.

Norland Elite, Hologic Horizon, and iDXA. Adapted from Shepherd JA, Ng BK, Sommer MJ, Heymsfield SB, “Body composition by DXA,” Bone 104 (2017) 101–105. Copyright (2020), with permission from Elsevier.

When discussing BC data on a group basis, more accurate results for FFM (r > 0.95, SEE <1.98) were found (38). When assessing FM, FFM, or %FM changes of individual athletes, it is of importance that small changes may be detected accurately, and not as stated by Santos, Silva, Matias, Fields, Heymsfield, and Sardinha (38): *“… an athlete that gains about 5% FM the estimation error can be 5+1.62% or 5-1.62%, this represents an error of about 50% in the %FM changes in this athlete”* (38). Van der Ploeg, Withers, and Laforgia demonstrated in their study (81) (comparison of BC by DXA with that of 4-C model, measured at 152 healthy adults) that the bias for %BF compared between DXA and a 4C model decreased with increasing BF. As an example, when BF was 10 % using DXA, BF using a 4-C model was 13 %, and when BF using DXA was 30 %, the percentage of BF with 4-C model was nearly the same, namely 30.3 %. According to Van der Ploeg G.E. et al. (81)*:”These body fat scores in combination with Fig. 1 demonstrate that DEXA tends to progressively underestimate the body fat of leaner individuals compared with the 4C model.”* Therefore, BC results in lean athletes (cross-sectional study or longitudinal study), especially after specific training or nutritional interventions, should be interpreted with caution when using DXA approaches. As with all BC approaches, when undertaking DXA scans, a standardised protocol (78) including subject presentation and correct positioning is important in order to minimise measurement errors. The authors Nana, Slater, Hopkins, Halson, Martin, West, and Burke (82) demonstrated in their study that best practice protocols using DXA for BC assessment in athletes minimize biological and technical errors. Changes in the hydration status of body tissues due to different exercise protocols (83) or food and fluid intake, as well as different positioning protocols (84) may increase potential errors (82). How to perform DXA scans for generating BC results, possible strengths and limitations of this technology may be found elsewhere (78).

- _Ultrasound:_ In 2012 Ackland and colleagues reviewed various BC methods, their strengths and possible weaknesses and found US B-mode (brightness mode) imaging as a promising method for future studies due to its excellent measurement accuracy (2). The accuracy of measuring SAT thicknesses using US is about 0.1-0.2 mm at 12-18 MHz probe frequency (7, 8, 22) when the correct speed of sound of 1450 m s^{-1} (85) for SAT distance calculation is applied. Higher frequency (e.g., 10 to 18 MHz) increases image resolution. In 2013, Müller et al. (7) compared SFs with US thickness measurements and found that the eight commonly used ISAK sites (triceps, subscapular, biceps, supraspinale, iliac crest, abdominal, front thigh, and medial calf) should not be used for US imaging. The sites on the trunk (subscapular, supraspinale, iliac crest, and abdominal site) were not be found easily evaluable, and therefore, a modified protocol for US measurements has been recommended. Recently the IOC Working Group on Body Composition, Health and Performance introduced a standardised protocol for measuring SAT thicknesses. The new set of sites represents the trunk, arms, and legs. These sites are relative to the individual's stature and should be marked according to a defined protocol (8) (see Table 11, and Figure 7 in the Material and Methods section). As with other BC methods it is highly recommended to follow a standardised protocol to obtain maximum accuracy and reliable results (95% of SAT thickness sums were within ±1.1 mm for the sum of eight sites (D_I), SEE = 0.55, $R^2 = 0.998$, $p<0.01$; Index I when embedded fibrous structures are included in the SAT thickness values) as has been found in this study (8). Furrowed SAT borders (biologically given limitations) and inaccuracies by the observer may limit this method's use. Störchle, Müller, Sengeis, Ahammer, Fürhapter-Rieger, Bachl, Lackner, Mörkl, and Holasek (9) applied the standardised US protocol in a group of participants with BMI values between 18.6 and 40.3 kg m^{-2} (from normal weight range to obese class III according to the World Health Organisation (WHO)) to study intra-observer reliability. Two observers performed three measurements on each participant (12 women, 26 men) within one week, with the following results: SEE = ±1.1 mm for D_I, 95% of D_I were within ±2.2 mm and Spearmen's rank correlation coefficient (ρ) was 0.999 (p<0.01); for D_E (Index E excluded embedded fibrous structures in the SAT thicknesses) SEE = 1.5 mm; 95% of D_E were within ±3.2 mm and ρ was 0.997 (p<0.01). Absolute deviations of the normal weight group, 95% of D_I were below 1.4 mm, and in the overweight/obese group, below 2.9 mm. Relative deviations (in percent of SAT) were smaller in the overweight and obesity groups. Inter- and intra-observer reliability was recently examined in an international multicentre study (22). The standardised US method for measuring SAT thicknesses was applied for 76 female and male athletes of various sports in five different study centres (22). Results indicate that the inter-measurer reliability differs between experienced and inexperienced observers. The deviations of the three experienced observers of each of the two study centres from their mean for D_I was lower (LOA = 1.2 mm, SD = 0.60 mm) than for inexperienced observers (LOA = 3.1 mm, SD = 1.6 mm). A detailed discussion about reliability (inter- and intra-observer) of the novel standardised US method for measuring SAT thicknesses in athletes, non-athletes, and also applied in children may be found elsewhere (8-10, 22, 86). Bazzocchi, Filonzi, Ponti, Albisinni, Guglielmi, and Battista (87) reviewed a complete overview of often used measurements of adiposity using ultrasound (e.g., intra-abdominal fat thickness) entitled *"Ultrasound: Which role in body composition?"* and concluded that US is an ideal method for evaluating young patients, and for follow-up studies.

- Medical Imaging, *Magnetic Resonance (MRI),* *and* Computer Tomography (CT): measure adipose tissue (AT) on the anatomical level (according to Wang et al., at Level IV, the tissue-system level (11)). Shen W, Wang ZM, Punyanita M, Lei J, Sinav A, Kral JG, Imielinska C, Ross R, and Heymsfield SB (88) pointed out that "adipose tissue" (at the tissue-organ level) and "fat" (lipid at molecular level) should not be used as similar terminology. AT counts loose connective tissue that is loaded with adipocytes, while "fat" is usually lipid in the form of triglycerides (88). Up to 80 % of AT is fat, and about 20 % is water, protein, and minerals (88). MRI and CT are capable of quantifying AT volume as voxels or volume elements to measure AT content and distribution (88, 89). The imaging tool MRI is widely used for estimating the SAT and AT in deeper depots: in organs (liver, pancreas, kidneys, heart) and muscles (89, 90). The whole MRI body-protocol was introduced in 1992 by Ross R., Lèger L., Morris D., de Guise J., and

Guardo R. (91). These authors found MRI to be a practicable and reliable (AT volume changes between two tests ranged from 0.9 to 4.3 %, and 1.4 to 4.2 % for area measurements of AT, taken at the L4-L5) tool for assessing total and reginal AT in humans (91). Since the validation study by Abate N., Burns D., Peshock R.M., Garg. A., and Grundy S.M. in 1994, the interest in MRI imaging techniques has grown (89). Abate et al. analysed the accuracy and precision of MRI by comparing the mass of SAT and intraabdominal AT (IAAT) using MRI with the same mass obtained after dissection measurements of three cadavers (via direct weighing). The LOA between MRI and dissection measurements were -0.066 kg and +0.218 kg; the coefficient of variation (CV) of multiple repeated estimates of mass was <14 % (92). The CV for repeated SAT measurements by CT and MRI are similar by about 2 % (88). The well-known CT and MRI protocols are not capable of measuring all AT compartments (e.g., visceral AT, intrathoracic AT, extra-pericardial, extra-peritoneal). In addition to VAT volume measurements by multiple-slice or whole body protocols, single-slice studies for measuring VAT have often been used due to lower costs and no exposure to radiation compared to CTs (88, 93). Authors have studied the predictive value of masses of different compartments in the abdominal region and computed from single-slice images the total mass of the relevant compartment (93) with reduced accuracy. To date, different MR methods have become available for measuring AT distribution in humans, and several advantages over CT have been discussed: lack of ionizing radiation, ability to estimate volumes in contrast to areas, better definition of AT) (92); fat may be distinguished easily due to bright fat signals (short (T_1) longitudinal relaxation time) compared with lean tissue compartments (94), but the possibility for frequently application in elite athletes is still limited.

According to the above-mentioned study of Meyer et al. (4), in practice, a diverse range of BC methods were in use (until 2013). Results in this study showed that more than 10 % of all respondents related to BC assessments used MRI, CT, 3D laser body scanner, lipometer, 4-C model (including DXA, Bod Pod, deuterium dilution), somatotyping, five-way fractionation model, and deuterium dilution for estimating TBW and FFM (N=147) (4). A very short introduction into 3D body scanning, the 'Lipometer', and for assessing TBW, the deuterium dilution technique is given here.

- Three-dimensional (3D) whole body scanning: is a growing approach to measure anthropometric variables in the fitness and health industry. Fixed or portable 3D scanners are used (Figure 4) to determine body volume, body lengths (e.g., upper arm, lower arm), surface area, circumferences at the trunk, and extremities. To achieve the most accurate results, a standardised protocol during scanning process is important (26). To my knowledge, there is no recognised training course or training system for scanning human bodies although published guidelines of different manufacturer may be found on manufacturer websites.

Figure 4: 3D Scanning using a portable 3D scanner (Artec Eva)

Carter, and Stewart dedicated a whole chapter in the book “Body Composition in Sport, Exercise and Health”, edited by Stewart and Sutton (95), about somatotyping and 3D scanning. The authors compared the well-established and standardised surface anthropometry (27) with 3D scanning as a more recent approach for measuring skeletal lengths, circumferences, and breaths (96). Another introduction to 3D scanning including its advantages and possible disadvantages may be found elsewhere (24).

- <u>Lipometer:</u> an optical device termed ‘the Lipometer’ (Moeller Messtechnik, Graz, EU patented) is a non-invasive tool used to measure SAT thickness layers at 15 defined body sites in humans (97). A validation study of the results using the Lipometer and technical features of this method was published elsewhere (98). In this study, the SEE for %BF using the Lipometer (SAT topography of 15 defined SAT layers) compared to DXA as the criterion method was 2.59 % in males and 3.72 % in females. According to Lohman et al. (41), a SEE larger than 3.5 % means that the error rate of the applied technique is too high to be acceptable. Santos and colleagues found in their study that DXA may not be accurate enough to track small changes in adiposity in elite athletes

(38). Therefore, using DXA as the criterion method may be not recommended to validate new BC approaches.

- Dilution methods: are used as the reference method for estimating TBW as the largest single compartment (~ 60 %) of the human body (31, 99). In vivo TBW (distributed into intracellular and extracellular compartments) can be measured based on the dilution principle. For achieving accurate and precise results of TBW measurements best practice protocols overseen by the International Atomic Energy Agency should be carefully adhered (https://humanhealth.iaea.org, (100)). According to Ellis (31) the most direct technique for estimating TBW is the dilution principle, *"using a tracer dose of labeled water (tritium, deuterium, or oxygen-18) and collection of two body fluid samples (blood, urine, or salvia), one predose and second after an equilibration time of ~2-3 h. The method of analysis is dependent on the choice of tracer: radioactive β-counting for tritium, mass spectroscopy for ^{18}O, and infrared absorption, gas chromatography, or mass spectroscopy for deuterium"(31).* The estimated errors for TBW measurements achieved for each of these tracers is below 1 kg. Intra-observer CVs and TEM are reviewed by Lee, Brandon, and Lohman (101). The reported CVs for %Fat in children were 0.8 % and 1 % in adults. Based on three trials the TEM for TBW was 1 %, or 0.5 L. The test–retest CV in 10 elite athletes for TBW was 0.3 % (102). Measuring BC in elite athletes to monitor small changes of %BF, or FFM, the 4-C model (including dilution techniques for estimating TBW) is recommended based on accuracy reasons and is considered as the reference method (38, 51, 103) for those measurements. Commonly used BC methods applied in athletes and further features are listed in Table 9.

Table 9: Commonly used BC Methods in athletes, accuracy, reliability, and further features.

Adapted with permission from Slater G, Shaw G, and Kerr A. Athlete Considerations for Physique Measurement, in Best Practice Protocols for Physique Assessment in Sport, edited by Hume P.A., Kerr D. A., Ackland T.R. (Springer, Singapore, 2018) p. 50 (42).

Technique; commercial availability	Accuracy; reliability	Regional assessment	Attributes measured	Time commitment; minimum assessment frequency	Athlete friendly; health risk	Skilled technician required
Surface anthropometry; very available	Medium; high	Possible but not recommended	FM (via equation), ΣSF	Moderately quick <15 min; 3 weeks	Very; low	Yes
BIA, BIS; very available	Low; low	invalid	FFM, FM, TBW	Very quick <1 min; 4 weeks	Very; low	Ideally
DXA, available	Medium; high	Possible and reliable	NOL, BM, FM	Quick <10 min; 8 weeks	Very; medium	Yes
Bod Pod or ADP, UWW; available	Medium; high	Not possible	FFM, FM, TBV	Quick <10 min; 4 weeks	Very; low	Ideally
US; hard to find	High; medium	Possible and reliable	mm of fat (22)	Quick; 4 weeks	Very; low	Yes
3D scanning; available	Unknown	Possible	FFM, FM, TBV, SV	Very quick <5 min; 4 weeks	Very; low	Yes
Deuterium dilution; very hard to find	Medium; high	Not possible	TBW, FFM, FM	Very slow ~6 h; 4 weeks	Somewhat; low	Yes
3-C methodology; hard to find	High; high	Not possible	FM, NOL, BM	Slow ~1 h; 4 weeks	Somewhat; medium	Yes
4-C methodology; hard to find	High; high	Not possible	FM, MM, RM, BM	Very slow ~6 h; 8 weeks		Yes
Recent improvements						
US; available (8, 22, 86)	High; high (8-10)		TSAT (28)			Yes (22)
DXA			VAT (104, 105)			

Abbreviations: (BIA) bioelectrical impedance analysis, (BIS) bioelectrical impedance spectroscopy, (DXA) dual-energy X-ray absorptiometry, (ADP) air displacement plethysmography, (US) ultrasound, (3-C) three-compartment methodology, (4-C) four-compartment methodology, (UWW) underwater weighing, (BM) bone mineral content, (FM) fat mass, FFM fat-free mass, MM muscle mass, NOL non-osseous lean (RM) residual mass, SV segmental volume, (ΣSF) sum of skinfolds, TBV total body volume, TBW total body water, VAT visceral adipose tissue.

2 Material and Methods

The present thesis, entitled “Anthropometry and Subcutaneous Adipose Tissue Patterning in Elite Athletes: Application of a Novel Ultrasound Method” represents primarily the main findings of two published research articles using the recently standardised US measurement method for measuring SAT thicknesses in international competing elite judokas (Sengeis et al., 2019 (58)) and Kenyan long-distance runners (106). The main findings of the published articles are integrated and discussed in this thesis, with the permissions of the journals. Further, this thesis includes anthropometric results and SAT patterning of female and male athletes competing in various sports. To clarify the framework of the results this part of the thesis is organized into three sections.

SECTION 1:

includes results of elite female and male judokas (study 1 and study 2 in Table 10:).

Study 1: *“Sixtyone elite judokas participated in this study, of whom 50 had competed at an international level (14 medallists of Olympic Games, World Championships, Masters, Grand Slam and Grands Prix during 2015-2017), 10 athletes participated in the Olympic Games in Rio de Janeiro 2016, and two won Olympic medals there. Females and males are analysed separately because of their deviating physiological conditions and body composition necessities* (1, 107). *The study was approved by the Ethics Committee of the Medical University of Graz (20-295ex08/09). All participants (or parents of participants younger than 18 years) were informed about the study contents and aims and signed a written consent form before the examination was started. 51 athletes were measured within 3 days, before the upcoming competition phase (during an international training camp in Mittersill, Austria, January 7-9, 2016), ten were measured in the following weeks. The most important first competitions for the investigated group of athletes took place on January 30-31 (European Open) and on February 6-7 (Grand Slam, Paris)”(58).* The whole group (N=61) were separated by sex, into youth or adult females and males, and heavy weight categories (females: +78 kg and for cadet females +70 kg; males: +100 kg) in Table 12. This study was published by Sengeis et al., 2019 (58).

Study 2: includes 13 female, and 18 male elite judo athletes. This study was conducted on the day before the official weigh-in for an international judo event (European Open (EO) in Oberwart Men, February 16-17, 2018, and Woman February 15, 2019). The official weigh-in for each weight category (WC) was held the evening before the competition day (official scales were available for test weigh-in on Friday and Saturday (08:00 am to 10:00 pm) before competition (except during the official weigh-in from 07:00 to 07:30 pm). Section 1 includes comparisons of SAT thickness sums in terms of D_I of a sub-group of eight female judokas measured at two different times. The eight female judokas took part in the study in Mittersill, 2016, and for a second measurement series on the day before the official weigh-in before competition (EO, Oberwart, 2019).

SECTION 2:

Study 3: *"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* (Table 10:). *The group of Kenyan athletes included 7 female and 25 male long-distance runners. The four mountain runners (*number 3, 9, 19, 22 in Figure 24*) 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 to the Ethical Standards in Sport and Exercise Science Research: 2020 Update (108) and approved by the ethics committee of the Medical University of Graz (20-295 ex08/09)".* This study was published by Sengeis et al., 2020 (106).

SECTION 3:

Study 4: includes results of a large study sample (N=272, 38.6 % females, and 61.4 % males) of international elite athletes performing in different sports, including combat sports, endurance sports, ball sports, and shooting (see Table 16). All the participants included in this study competed at the international level. Participants (including heavy weight categories in combat sports of both sexes) ranged in age from 18 to 58 years, body height from 152.6 to 202.2 cm, body mass from 43.5 to 133.2 kg, BMI from 16.1 to 39.5 kg m^{-2}, MI_I from 17.3 to 39.2 kg m^{-2}, and SAT thickness sums (D_I) from 3.0 to 145.4 mm. Anthropometric measurements and the recently introduced standardised ultrasound method were used to assess possible differences between athletes in different sports. The findings are presented in Section 3.

Participants, Study Design, and Observer

The main results of this study used a cross-sectional design (see Table 10:). A longitudinal study design was performed for comparisons of a sub-group of nine Kenyan long-distance runners and eight female judokas to analyse possible differences when measuring athletes at two different time points. Table 10: summarized the basic characteristics of each study regarding sampling and design.

Table 10: Sampling and Design of Each Study included in This Thesis.

Study	Sample	Sex	Design (Date)	Published
1	Judoka (n=61)	26 females, 35 males	Cross-sectional: while an international training camp in Mittersill, Austria, January 7-9, 2016, 10 were measured the following weeks.	Yes SJMSS(58)
2	Judoka (n=31)	13 females, 18 males	Cross-sectional: immediately before the official 'weigh-in' before competition (European Open in Oberwart Men: February 16-17, 2018, and Women: February 15, 2019). Longitudinal: comparison of a sub-group of eight elite female judokas who were measured while an international training camp (study 1), and three years later in Oberwart February 16, 2019; on the day of the official 'weigh-in' before competition.	No
3	Kenyan long-distance runners (N=32)	7 females, 25 males	Cross-sectional: Kenya, April 8-14, 2017 Longitudinal: sub-group of nine male athletes, 18 weeks later, Austria, August 31, and September 1, 2017.	Yes IJSM(106)
4	Elite athletes from 11 sports (N=272)	105 females, 167 males	Cross-sectional: January 2016 to June 2019, including judokas and Kenyan long-distance runners.	Parts (1+3)

Abbreviations: (SJMSS) Scandinavian Journal of Medicine and Science in Sports, (IJSM) International Journal of Sports Medicine.

The study was approved by the Ethics Committee of the Medical University of Graz (20-295ex08/09). All participants were informed about the study contents and study aims and signed a written consent form before the BC measurements (anthropometry, skinfolds, and ultrasound imaging) were conducted. Two experienced observers performed the measurements in study 1. One of these two observers performed the measurements in study 2, 3, and 4. The observers had been trained according to the ISAK protocol for skinfolds and anthropometric measurements, and by the International Association of Sciences in Medicine and Sports (IASMS) for the US measurement technique.

2.1 Anthropometric Measurements

In this thesis anthropometric measurements were used to assess dimensions of the athletes by looking at the body height (head in the Frankfurt plane; horizontal plane between the lower edge of the eye socket to the tragus of the ear; Anthropometer GPM 119), body mass (Seca Modell 799), and circumferences (metallic tape CESCORF, Quick Medical QM 14200). In addition to SAT patterning, using US some anthropometric characteristics is essential for discussing the results in terms of health and performance optimisation strategies. Here, SFs were only used to identify possible differences between US sums and SF sums in elite judokas (study 1 in Table 10:). Therefore, in addition to the US body site description, all measured SF sites were listed below.

Circumferences:

The circumferences of the biceps (*b*), waist (*w*), and gluteal (hip) girth (*g*), were measured according to the International Society for the Advancement of Kinanthropometry (ISAK) protocol (27); the front thigh (FT) girth (*t*) was taken according to the International Association of Sciences in Medicine and Sports (IASMS) certification scheme (iasms.org). The landmarking procedure for the FT may be found in (8) or below in Table 11. When measuring the circumferences of the body it is important that the tape measure is even and straight. All measurements were taken with a non-elastic measurement tape without compressing the skin.

Figure 5: Biceps girth – flexed and tensed; according to the ISAK protocol (27).

Arm girth (biceps flexed and tensed) (b)

For measuring the peak of the maximally contracted biceps, the participant raised the arm anteriorly to the horizontal. The tape was positioned perpendicular to the long axis of the arm (27).

Waist girth (w)

The narrowest point between lower costal (10th rib) boarder and iliac crest, perpendicular to the long axis of the trunk were taken (27). The participant assumed a relaxed (upright) standing position, crossed the hands on the shoulders, and the tape was passed around the abdomen (horizontal, using a cross over technique). The measurement was taken at the end tidal position without compressing the skin.

Gluteal (hip) girth (g)

The participant stood with the feet together (or maximum hip width apart). A horizontal measure was taken at the maximum circumference of the buttocks (greatest posterior protuberance) perpendicular to the long axis of the trunk (27).

Thigh girth at the front thigh site (t)

As mentioned above, this measurement was taken according to IASMS protocol (see Table 11). The girth was measured perpendicular to the axis of the thigh at the body site of the front thigh (FT) (8). The right foot was placed on a supporting box, the thigh in the horizontal position, and the lower leg in vertical position. For measuring the thigh girth the landmarking of the FT site according to (8) should be undertaken first.

Skinfolds

In this thesis SFs were measured for comparisons between US sums and SF sums in elite judokas. All measurements were taken according to ISAK (27) protocol on the right side of the body. All SF landmarks were located carefully. A skinfold or "pinch" was taken perpendicular to the skinfold orientation. A double fold of skin plus the underlying SAT was held between the left thumb and left index finger (Figure 6). The calliper was held at 90° to the surface of each marked body site (1 cm away from the grasped skinfold). Measurements were recorded two seconds after full pressure (Harpenden Skinfold Calliper, Baty International, spring pressure of 10 g/mm^2) was applied. SFs were measured at eight body sites: triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh, and medial calf. A further description of the site marking procedure may be found in the ISAK manual (27).

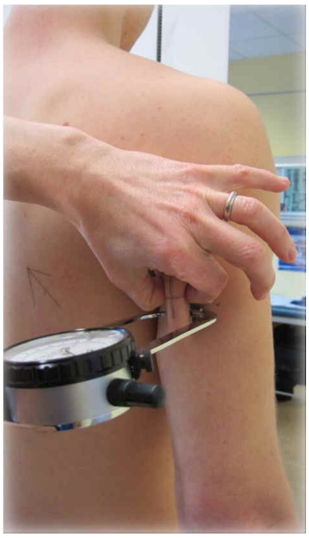


Figure 6: Skinfold measurement of the triceps side using a Harpenden Calliper.

2.2 Ultrasound Site Marking

For all data collection of this thesis, all eight standardised sites were marked according to a standardised protocol (8). Marking procedures were done in standing or sitting position on the right side of the body. All distances (*d*) are percentages of the individual`s body height. The eight body sites are as follows: upper abdomen (UA), lower abdomen (LA), front thigh (FT), lateral thigh (LT), medial calf (MC), erector spinae (ES), distal triceps (DT), and brachioradialis (BR).

Table 11: Description of US measurement sites and measurement procedure (Figure 7).

Adapted from "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, Müller W, Lohman T.G., Stewart A.D. et al., Br J Sports Med 2016; 50:45–54"; with permission from BMJ Publishing Group Ltd.

Site name	**Description of the sites; marking is done in standing or sitting position, on the right side of the body; see (Figure 7). All distances (*d*) are percentages of stature *h***	**Notes on US image capture; all US measurements in supine position. Always use a thick layer of US gel (at least 3–5 mm)**
UA Upper abdomen	1. Mark a vertical line at a distance d=0.02 h (i.e., 2% of body height *h*) **lateral** to the centre of the umbilicus 2. Project vertically and mark a horizontal line at d=0.02h **superior** to the umbilicus. (In case this site is above a tendinous inscription of the rectus abdominis (where subcutaneous adipose tissue (SAT) is thicker), move the probe some millimetres to the end of this inscription and measure the thickness there)	Lying in **supine** position; have the participant stop breathing a mid-tidal expiration and then capture the image
LA Lower abdomen	1. The same line (1) as for the upper abdomen 2. Project vertically and mark a horizontal line at d=0.02 h **inferior** to the umbilicus. Measure always exactly at this point	Lying in **supine** position; have the participant stop breathing at mid-tidal expiration and then capture the image

EO External oblique	1. Locate and mark the anterior superior iliac spine (ASIS) 2. The participant assists by holding the end of the tape at the apex of the costal arch at the **inferior** margin of the sternum (where it meets the xiphoid process). The participant looks ahead! 3. Draw a line from the ASIS in the direction of the costal arch 4. Mark a perpendicular line at d=0.02 h from ASIS	Lying in **supine** position; capture the image with the probe held in the direction of the perpendicular line
ES Erector spinae	1. Mark a **transverse** line at d=0.14 h above the solid surface (table) on which the person is sitting in a stretched upper body position with thighs horizontal and legs unsupported	Lying in **prone** position
DT Distal triceps	1. Put the lower arm on a support surface (table) with the hand in the mid-prone position; mark a **vertical line** on the most posterior aspect of the arm. 2. Mark the site on the **vertical line** at a distance from the surface of d=0.05 h	Lying in **prone** position; capture the image with the dorsal surface of the hand on the table. Make sure the probe orientation is perpendicular to the skin
BR Brachioradialis	1. The participant puts a forearm with the hand in the mid-prone ('shake hand') position on a support table and contracts the brachioradialis (e.g., against a resistance provided by the hand of the measurer). 2. Draw a longitudinal line on the most anterior surface of the brachioradialis muscle 3. Mark a transverse line at a distance d=0.02 h distally from the anterior surface of the biceps brachii tendon (press the end of the metre rod onto the stretched tendon). Project this line transversely to intersect with the longitudinal line	Lying in **supine** position; take the image with the arm in a mid-prone position and in contact with the thigh (muscles of the arm are relaxed); avoid imaging the vein in case there is one in the vicinity
FT Front thigh	1. Put a foot on the anthropometric box which is placed in front of a wall such that the thigh is horizontal, and the big toe and the knee touch the wall. 2. Mark the site at a **horizontal** distance d=0.14 h from the wall	Lying in **supine** position
MC Medial calf	1. Place a foot on the anthropometric box such that the thigh is horizontal and the leg vertical 2. Mark the site at **d=0.18 h** (individuals with exceptionally long legs, **d=0.20 h** should be used (according to (86)) above the surface at the most medial aspect (use a ruler to determine the most medial aspect when looking vertical down	Lying in **rotated** position; participant rolls onto the right side with the right knee at a 90° angle so that the lateral aspect of the right leg is supported
LT Lateral thigh	1. Draw a horizontal line on the lateral side of the thigh at the height of the gluteal fold (at the height of the fold at the most dorsal aspect of the thigh); 2. Mark the site on this line at the midpoint of the sagittal thigh diameter. Use a calliper for (1) and (2)	Lying in **rotated** position; participants rolls onto the left side with both knees at a 90° angle, with the right leg over the left leg

Athletes are always short on time; therefore, the over-all measurement time (US plus anthropometry) was kept as small as possible. The following procedure was chosen:

1. SAT protocol and declaration form were explained.
2. Anthropometric measurements, and landmarking procedure were performed.

m	[kg]	body mass
h	[m]	body height (stature)
l	[m]	leg length (ASIS* point to floor) * anterior superior iliac spine
LT		landmarking; standing position
s	[m]	sitting height
ES		landmarking; sitting in upright position
w	[m]	waist girth
g	[m]	gluteal (hip) girth
b	[m]	biceps girth flexed and tensed
UA, LA		landmarking; standing position
MC, FT		landmarking; right foot is placed on the anthropometric box
t	[m]	thigh girth (at the height of the FT body site)
BR, DT		landmarking; forearm on a support table

3. US imaging in different body positions (notes on US image capture, Table 11).
4. US image evaluation, and report creation.

All body positions for the US landmarking procedure and for measuring the sitting height are shown in Figure 7.

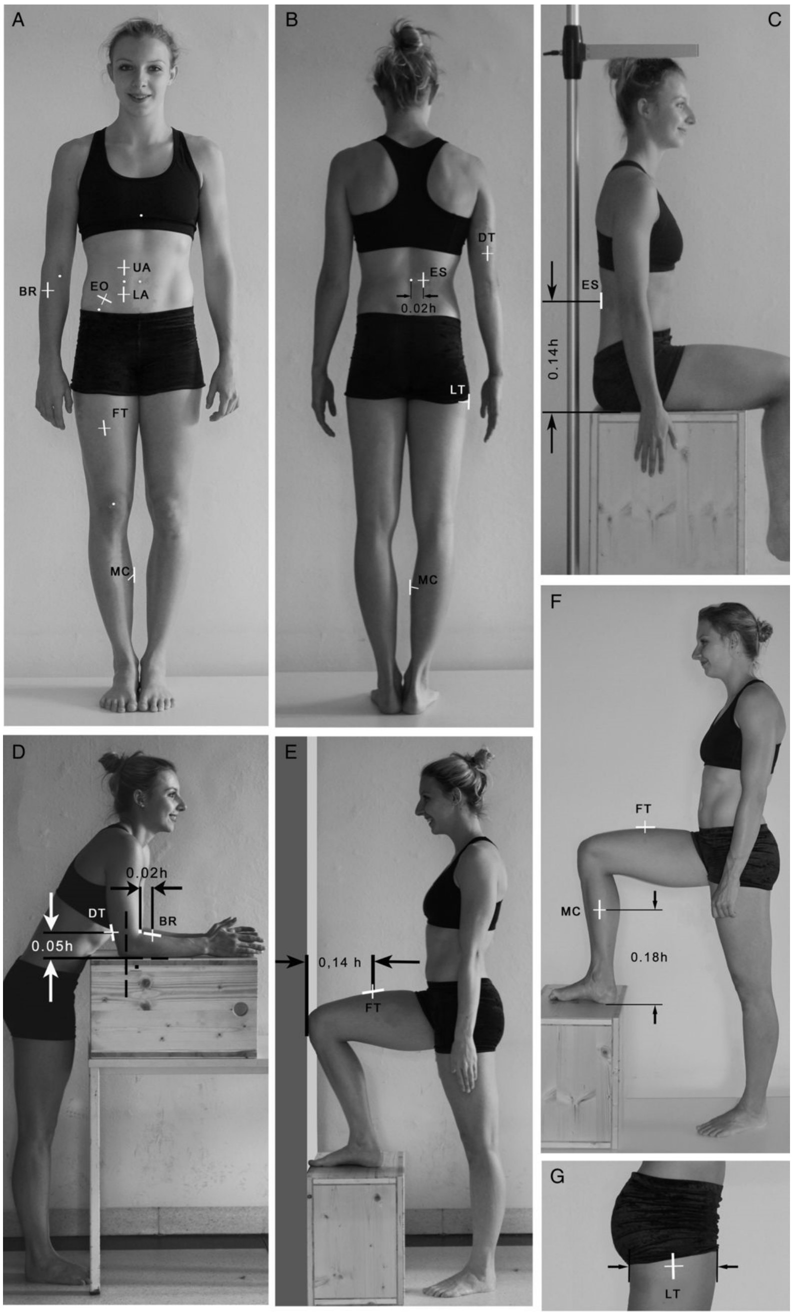


Figure 7: Standardised ultrasound body site landmarking procedure and different body position.

All ultrasound body sites (**A** and **B**) and different body position for landmarking procedure (**C-G**). (**C**) with notation showing how to mark the ES site and how to measure sitting height (*s*).
Reproduced from "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". Müller W, Lohman T.G., Stewart A.D. et al., Br J Sports Med 2016; 50:45–54; with permission from BMJ Publishing Group Ltd.

2.3 Ultrasound Imaging of SAT and Image Evaluation

After the marking procedure (~ 5–7 min) either standing or sitting, images were captured with the participant lying (on a plinth) in supine, prone or rotated (side-lying) position. Conventional US devices operating with linear probes (Phillips CX 50 linear probe L12-3, GE Logic e linear probe 18 L, and Alpinion E-CUBE i7 linear probe L3-12T) were used. To create an image, the middle of the probe (transducer) was placed over the marked body site. The US probe was placed perpendicular to the surface of the skin. Compression of the skin and underlying fat was avoided by using a thick layer of US gel (8, 47). After verifying that all relevant structures (see Figure 9) for SAT thickness evaluation may be seen on the screen the US images were stored. According to Müller et al., *"B-mode (brightness mode) US images are generated by sequences of US beams which penetrate the tissue to create an image in which the brightness of the screen corresponds to the echo intensity in the plane of the scan"*(8).

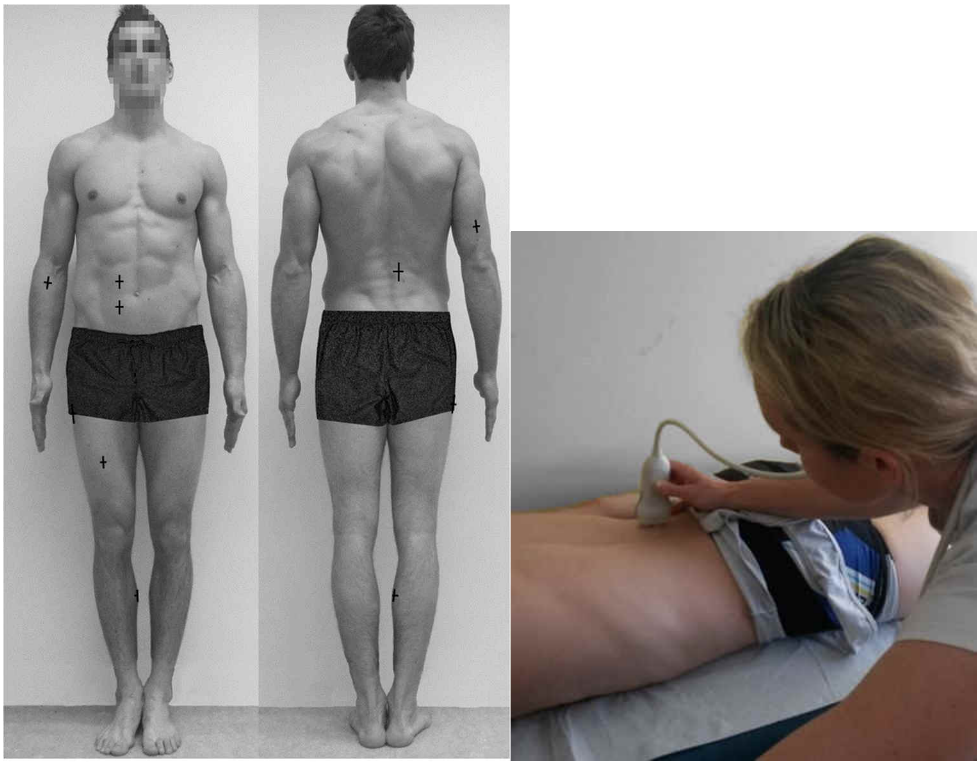


Figure 8: Landmarked eight body sites, and ultrasound imaging of the site erector spinae (ES).

Figure 8 shows US imaging procedure of the body site ES. The participant is lying in prone position. A thick layer of US gel (approximately 5 mm) was applied to avoid tissue compression. The US probe was held perpendicularly to the skin at the given site. The centre of the probe (marked with a grey line) was positioned exactly above the landmarking centre, which was previously marked.

2.3.1 US Evaluation of SAT thicknesses.

All ultrasound SAT thicknesses in this thesis were evaluated using a semi-automatic evaluation software (Rotosport, Austria; rotosport.at). For distance calculation in adipose tissue this software uses a sound speed of 1450 m s^{-1} (8, 85). Figure 9 A and B shows a typical US image -as an example- from the FT site. The chosen region of interest (ROI) in the shown image measured 235 individual thickness measurements which resulted in a robust mean (d_I) of 8.10 (±0.11) mm. The software automatically calculated mean, median, minimum, and maximum values of the analysed images. Sums of the eight standardised sites are termed (D_I) = $d_{I,UA} + d_{I,..} + \dots$ (index I indicates that embedded fibrous structures are included in the SAT measurements), and (D_E) = $d_{E,UA} + d_{E,..} + \dots$ (index E indicates that embedded fibrous structures are excluded in the SAT measurements). The sum of thicknesses (of all eight sites) of embedded fasciae (F) can also be evaluated: F= $(D_I - D_E)$. The percentages of F embedded in the SAT is $P = \frac{100 \cdot F}{D_I}$.

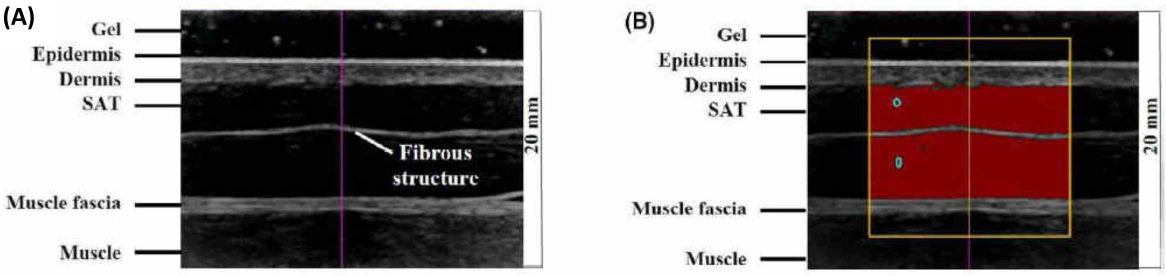


Figure 9: *"A, Typical example of an ultrasound image (US) of subcutaneous adipose tissue (SAT). Site: front thigh (FT). Tissue structures of relevance for US image evaluation are marked. B, The semi-automatic SAT detection algorithm starts out from the blue zones. The yellow frame represents the chosen region of interest. The evaluation algorithm measured automatically 235 SAT thicknesses of the SAT layer along 235 vertical lines in this image. Mean* d_I*=8.10 (±0.11) mm,* d_E*=7.61 (±0.12) mm, and the difference* d_F*=0.49 mm (represents the mean thickness of the embedded fibrous structure). Image depth was 20 mm"*(58). Reproduced from "Body weight and subcutaneous fat patterning in elite judokas, Sengeis M., Müller W., Störchle P. et al., Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc.

2.4 Statistics

Normality was analysed using the Shapiro-Wilk test, which showed that not all datasets were normally distributed. Descriptive statistics are shown as mean ± standard deviation (SD). A Mann-Whitney-U-Test or t-test (according to distribution) was calculated to analyse possible differences of D_I, D_E, and between female and male athletes separated by sports.

Spearman's rank correlation coefficients (Spearman's rho ρ or denoted by r_s) or Pearson's correlation coefficient (r) (according to distribution) were used to determine the relationships between BMI and MI_1 with D_I, and D_E, respectively, as well as relationships between running performance and D_I, and between running performance and MI_1. For determining statistically significant differences of D_I between group of sports the Kruskal Wallis test and pairwise comparisons (post-hoc Dunn-Bonferroni tests with adjusted p-values as well as calculated effect sizes ($r = z/\sqrt{N}$)) were used. The following intervals for r: 0.1 to 0.3 = small effect; 0.3 to 0.5 = intermediate effect; ≥0.5 = strong effect was taken (109). A paired t-test or Wilcoxon test (according to distribution) was applied for comparisons of E1 (BC assessment in Kenya) and E2 (BC assessment in Austria, 18 weeks later) in a sub-group of nine male Kenyan runners, and for comparisons in a sub-group of eight female judokas (TC, 2016 and EO, 2019). All data were analysed using IBM® SPSS® Statistics (Version 26).

2.5 Study Aims

The novel standardised US method enables taking SAT thickness measurements at an accuracy and reliability level not achieved by any other method. The selection of the new eight measurement sites was published recently (8).

The aims of this research were stated in the publication of 2019 (58):

- *"The sums of SAT thicknesses D (medians) measured by the standardised US method are larger in female than in male judokas.*
- *SAT thicknesses measured by US at the individual sites (medians) are not larger at all sites in female judokas than in male judokas.*
- *Relative body weight (measured in terms of MI_1 and BMI) correlates positively with D.*
- *There is a significant correlation between short-term weight losses for a competition and D measured some weeks before the competition.*
- *There is a significant correlation between short-term weight losses for an upcoming competition and SAT thicknesses measured some weeks before the competition at the abdomen sites.*
- *Percentages of fibrous structures embedded in the SAT are the same in both sexes.*

SF and US comparisions in 'elite judokas':

- *A higher skinfold sum of an athlete compared with another athlete is associated with a higher US sum D of SAT thicknesses.*
- *Thickness of SAT measured by US in individuals at a given site (d) can be estimated by SF measurements at this site (X) according to d=qX, with q being a constant factor, independent of the site and of the person measured".*

In addition: Kenyan long-distance runners (aims stated in the publication 2020 (106)):

- *"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 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 in the amounts of embedded fibrous structures (fasciae) between females and males?*

Further, the aim of this thesis is to compare D_I and D_E, percentages (P) of embedded fibrous structures, fat patterning, circumferences, and relative body weights (BMI and MI_1) in adult female and male elite athletes involved in eleven different sports.

3 Results

SECTION 1: Application of B-Mode US Method in Elite Judokas.

Published in Scan J Med Sci Sports, and were quoted literally, figure and table numbers were adapted to follow the correct order in this thesis. Figures and tables have been used with the permission from John Wiley & Sons, Inc.

Additionally, data obtained from elite judo athletes measured on the day of the official weigh-in before competition are also included in this section.

Table 12 represents anthropometric data, and SAT thickness sums (D_I, D_E, and fibres) using US in elite judokas. This table shows data of the whole group (N=61), or separated by sex, youth or adult, and heavy weight categories.

Table 12: Anthropometric Data of all Judoka Groups (Sengeis et al., 2019 (58)).

N	**G** 61	$\mathbf{G_f}$ 26	$\mathbf{G_m}$ 35	$\mathbf{G_{f,A}}$ 16	$\mathbf{G_{m,A}}$ 26	$\mathbf{G_{f,y}}$ 8	$\mathbf{G_{m,Y}}$ 6	$\mathbf{G_{f,HW}}$ 2	$\mathbf{G_{m,HW}}$ 3
a **[y]**	21.4 (5.5)	19.9 (4.2)	22.5 (6.1)	21.6 (3.7)	24.2 (5.8)	16.1 (1.0)	15.5 (1.0)	21.5 (7.8)	21.7 (4.2)
h **[m]**	1.730 (0.08)	1.678 (0.06)	1.769 (0.08)	1.681 (0.06)	1.763 (0.07)	1.655 (0.05)	1.739 (0.08)	1.745 (0.05)	1.879 (0.06)
s **[m]**	0.920 (0.04)	0.895 (0.03)	0.939 (0.04)	0.898 (0.03)	0.936 (0.03)	0.878 (0.02)	0.922 (0.04)	0.935 (0.00)	0.998 (0.04)
l **[m]**	0.966 (0.06)	0.936 (0.04)	0.990 (0.05)	0.934 (0.04)	0.982 (0.05)	0.928 (0.03)	0.999 (0.06)	0.987 (0.04)	1.039 (0.04)
M [kg]	75.6 (18.3)	64.7 (7.7)	83.7 (19.8)	65.3 (6.3)	82.1 (12.7)	59.6 (4.9)	67.1 (13.8)	80.3 (1.3)	130.6 (3.5)
BMI $\mathbf{[kgm^{-2}]}$	25.0 (4.0)	22.9 (1.9)	26.5 (4.5)	23.1 (1.6)	26.3 (2.7)	21.8 (1.4)	22.0 (2.5)	26.4 (1.1)	37.1 (2.4)
$\mathbf{MI_1}$ $\mathbf{[kgm^{-2}]}$	25.0 (4.0)	22.8 (1.9)	26.7 (4.3)	22.9 (1.8)	26.2 (2.8)	21.7 (1.5)	22.8 (2.3)	26.1 (0.3)	37.0 (2.3)
w/h **[1]**	0.44 (0.05)	0.42 (0.02)	0.46 (0.05)	0.42 (0.02)	0.46 (0.03)	0.41 (0.02)	0.41 (0.02)	0.43 (0.04)	0.56 (0.05)
C=*s/h* **[1]**	0.53 (0.01)	0.53 (0.01)	0.53 (0.01)	0.53 (0.01)	0.53 (0.01)	0.53 (0.00)	0.53 (0.01)	0.54 (0.02)	0.53 (0.00)
$\mathbf{D_{I,MEDIAN}}$ **[mm]**	49.8	66.1	21.8	65.4	20.8	65.9	19.0	115.4	111.5
$\mathbf{D_{E,MEDIAN}}$ **[mm]**	44.2	60.0	17.0	59.1	16.2	59.4	15.5	109.4	106.4
$\mathbf{P_{MEDIAN}}$ **[%]**	12.9	8.6	20.2	8.8	21.7	8.8	19.3	5.1	5.5

"Shown are means (±SD) of age (a), body height (h), sitting height (s), leg length (l) body mass (M), body mass index (BMI=M/h^2), mass index (MI_1=0.53M/(hs)), waist-to-height ratio (w/h) and the group medians of D_I and D_E. P is the percentage of fibrous structures $P=100F/D_I=100(D_I-D_E/D_I)$ of the group median. D_I: sums of subcutaneous adipose tissue (SAT) thicknesses when the fibrous structures are ***i****ncluded. D_E: sums of SAT thicknesses when the fibrous structures are* ***e****xcluded. F: sum of fibrous structures. Abbreviations: a: age [years], h: body height [m], s: sitting height [m], l: leg length [m], M: body mass [kg], BMI: body mass index [kgm^{-2}], MI_1: mass index [kgm^{-2}], w/h: waist-to-height ratio[1] , C: Cormic index [1]"*(58).

Adapted from "Body weight and subcutaneous fat patterning in elite judokas", Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc. Remark: Group definitions may be found in the Abbreviations.

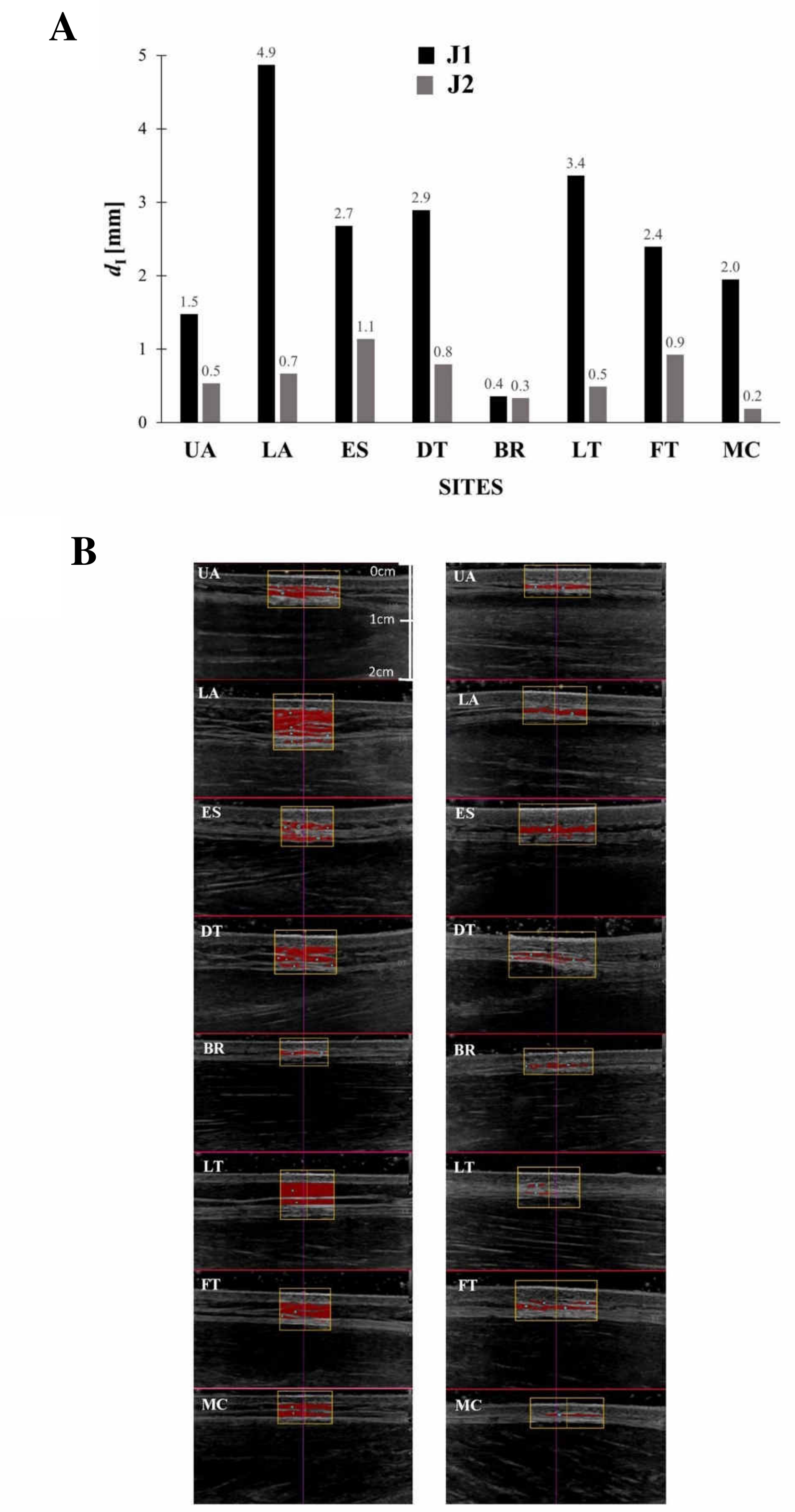


Figure 10: *“Comparison of Subcutaneous Fat Profiles” (Sengeis et al., 2019 (58)).*

Two elite male judokas, J1 (black columns; weight category (WC) 66 kg; body mass (M) 66.2 kg; body height (h) 1.751 m; BMI 21.6 kgm^{-2}*) and J2 (grey columns; WC 81 kg; M 84.0*

kg; h 1.824 m; BMI 25.2 kgm^{-2}) with almost the same sum of eight ISAK skinfolds (J1: 44.9 mm; J2: 45.4 mm) were compared. Their sums of SAT thicknesses measured by US differed enormously (J1: 20 mm, and J2: 5.1 mm). **A:** *The thickness values of J1 and J2 at the individual sites measured by US (d_I)* **i***nclude the fibrous structures.* **B:** *Shows the according series of evaluated US images (left side: J1, right side: J2). The yellow frame indicates the region of interest (ROI); in these two exemplarily selected participants, the numbers of measurements (semi-automatic thickness measurements) contributing to the representative mean at a given site ranged from 132 to 264.*
Reproduced from "Body weight and subcutaneous fat patterning in elite judokas", Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc.

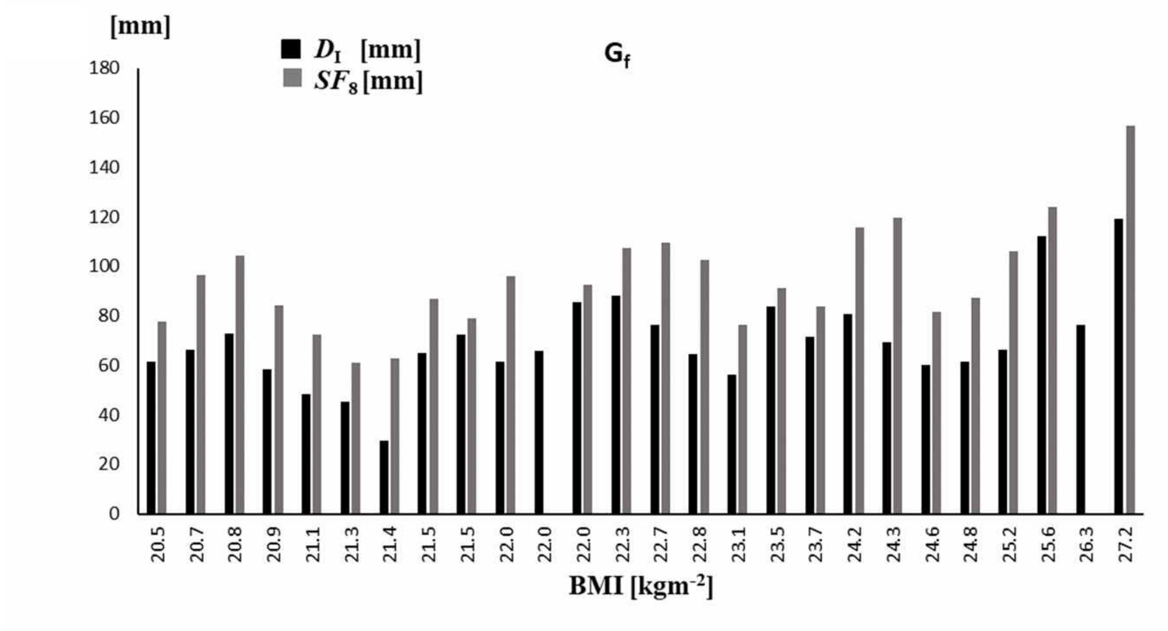


Figure11: *"Subcutaneous Adipose Tissue (SAT) Measurement with US and Skinfold (SF) Technique".*

Participants are ordered according to their body mass index (BMI). Black columns represent the D_I (sum of SAT thicknesses of the eight standardised US sites, with fibrous structures included); grey columns represent SF_8 (sum of the eight ISAK skinfold thicknesses) in all females (G_f). Reproduced from "Body weight and subcutaneous fat patterning in elite judokas", Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc (58).

Figure11 and Figure 12 (originally published in Sengeis et al. (58)) *"compare SAT thicknesses measured by US to skinfold (SF) measurements. Athletes are ordered according to their BMI. The pattern of the columns indicates that BMI and SAT are not correlated. This also holds true in many cases when SFs are compared to the US measurements of SAT (D_I). The ratios $D_{I,MEDIAN}/SF_{8,MEDIAN}$* was *0.61 for females (N_f=24), and 0.40 for males (N_m=30). However, several cases differed substantially from the medians of the ratios: for example, the male participant with BMI = 21.6 kgm^{-2} had a ratio of 20.0mm(D_I)/44.9mm(SF) = 0.45 and the male participant with BMI = 25.2 kgm^{-2} had a ratio of 5.1mm/45.4mm = 0.11* *indicating that the same skinfold sum (45 mm) did not at all correspond to the same SAT thickness sum measured by the standardised US technique (8, 9). SAT thickness sums ranged from 5.1 mm (corresponding to a mean of 0.64 mm) to 119.0 mm (14.88 mm) and SF sums from 44.6 mm (5.58 mm) to 175.8 mm (21.98 mm), see* Figure11 and Figure 12. *The FT and the MC site were the same for US and SF measurements. At FT, the ratios d/X ranged from 0.03 to 0.62 (median: 0.38; N= 55), and at MC from 0.03 to 0.64 (median: 0.37; N = 60). There was no constant factor relating the SAT thickness measured by US and by SF's, indicating the large influence of individual skin thickness and SAT compressibility on the SF measurement results"* (58).

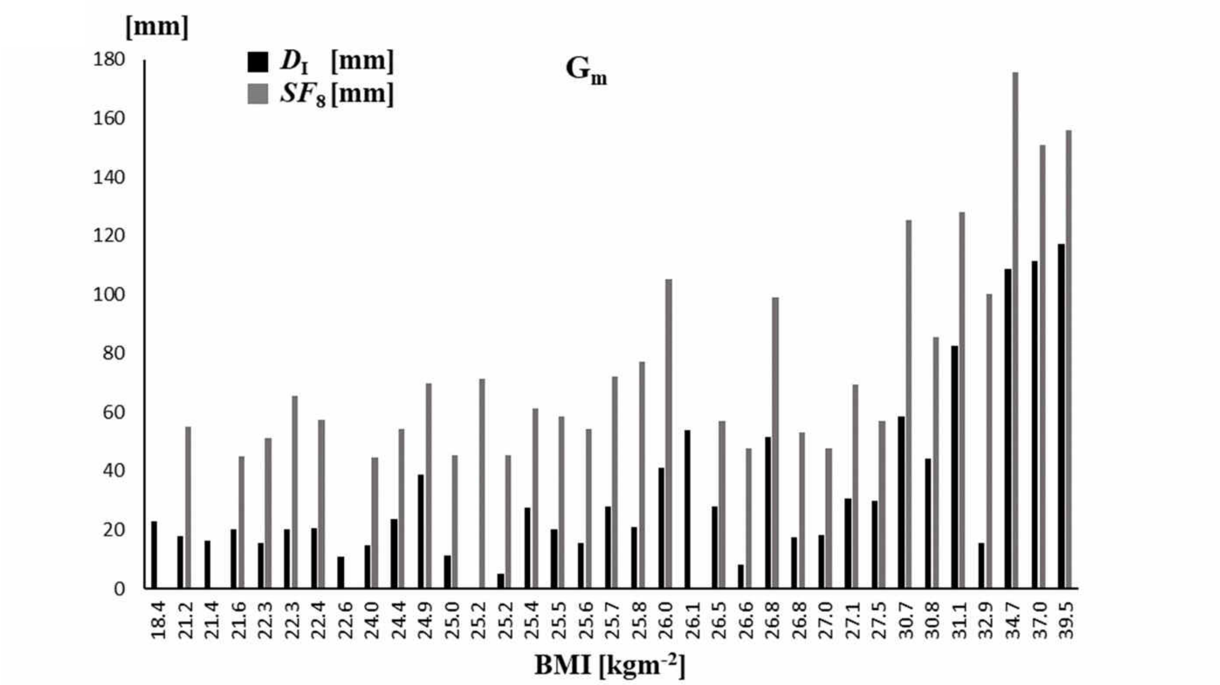


Figure 12: *"as in* Figure11*, but for all Men (G_m)"* (Sengeis et al. (58)).

Reproduced from "Body weight and subcutaneous fat patterning in elite judokas", Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc.

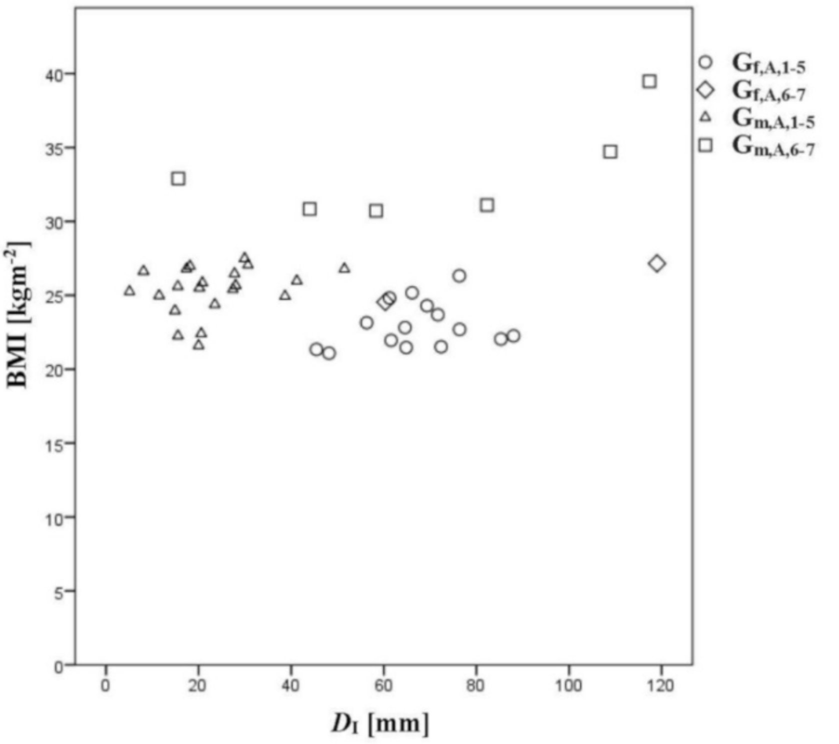


Figure 13: *“Relationship between the subcutaneous adipose tissue (SAT) and BMI”* (Sengeis et al. (58)).

The sum of US measurements of SAT thicknesses D_I *(with fibrous structures* ***i****ncluded) is compared to the BMI =M/h*^{2}*. For both female (*$G_{f,A,1-5}$*) and male (*$G_{m,A,1-5}$*) adult judo athletes together (i.e.: half-heavyweight and heavyweight not included), there was a weak negative correlation (ρ=-0.379, p<0.01) between BMI and* D_I*.*

$G_{f,A,1-5}$*: Female adults groups 1 to 5 (heavy weight,7, and half-heavweight,6, not included).*
$G_{f,A,6-7}$*: Female adults groups 6 to 7 (heavy weight,7, and half-heavyweight,6).*
$G_{m,A,1-5}$*: Male adults groups 1 to 5 (heavy weight,7, and half-heavyweight,6, not included).*
$G_{m,A,6-7}$*: Male adults groups 6 to 7 (heavy weight,7, and half-heavyweight,6).*
Reproduced from “Body weight and subcutaneous fat patterning in elite judokas”, Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc.

Figure 13 shows a negative correlation (ρ=-0.379, p<0.01) between the BMI and SAT thickness sums (D_I) when both sexes (excluding half-heavyweight and heavyweight) were analysed together. These results indicate that as a measure for relative body weight BMI is not a useful measure of fatness in elite athletes. *“Analysis of females and males separately did not result in a significant correlation”*(58).

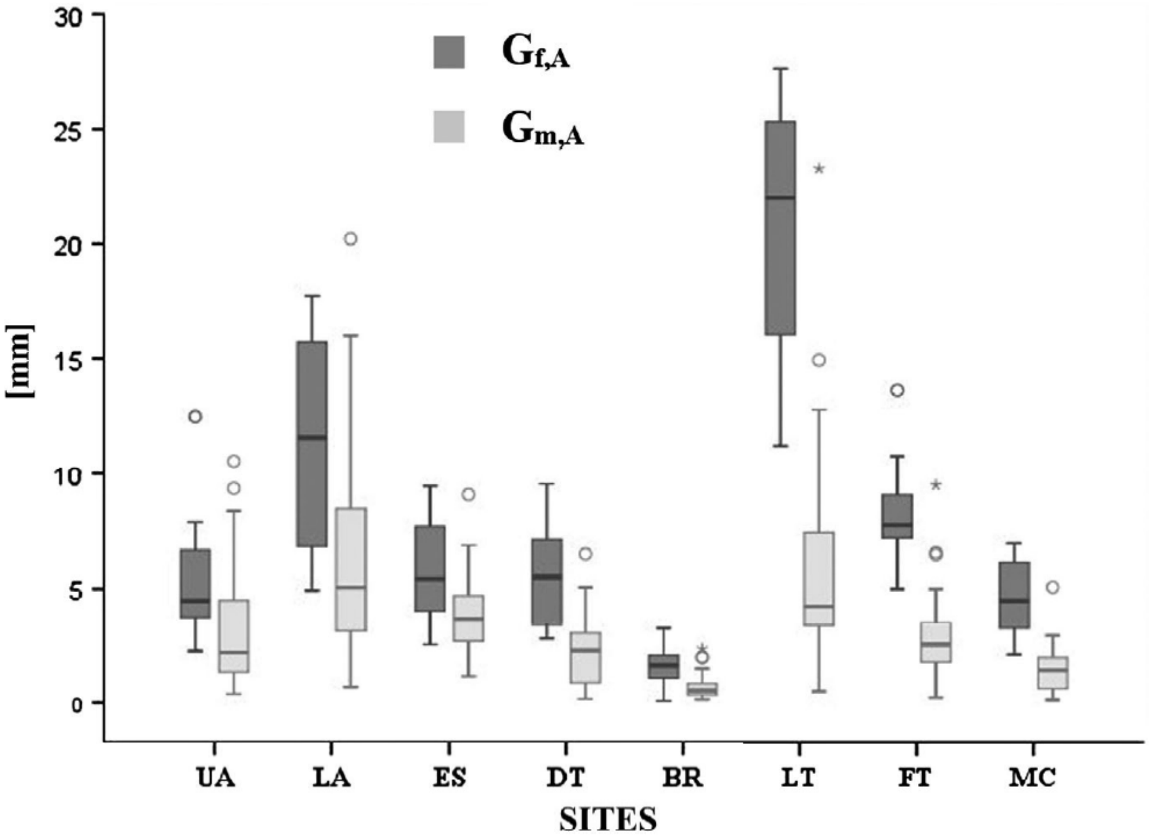


Figure 14: Adipose tissue thickness patterning in adult female ($G_{f,A}$) and male ($G_{m,A}$) judoka (Sengeis et al. 2019 (58)).
Abbreviations: (UA) upper abdomen, (LA) lower abdomen, (ES) erector spinae, (DT) distal triceps, (BR) brachioradialis, (LT) lateral thigh, (FT) front thigh, (MC) medial calf. Reproduced from “Body weight and subcutaneous fat patterning in elite judokas”, Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc.

Figure 14 shows SAT thickness patterning in female and male judokas. At all measured body sites, there was a significant difference between adult female and male elite judokas. The ratios of d_I median (including fibres) of all adult females and males were as follows: *“UA (4.9mm/2.2mm=2.2), LA (12.1/5.1=2.4), ES (5.9/3.7=1.6), DT (6.0/2.3=2.6), BR (2.1/0.5=4.2), LT (22.5/4.2=5.4), FT (8.2/2.5=3.3), and MC (4.9/1.4=3.5). The highest ratio (5.4) was found at LT”* (58).

3.1 Anthropometry, and SAT Measurements of Elite Judokas at their Selected Weight Category.

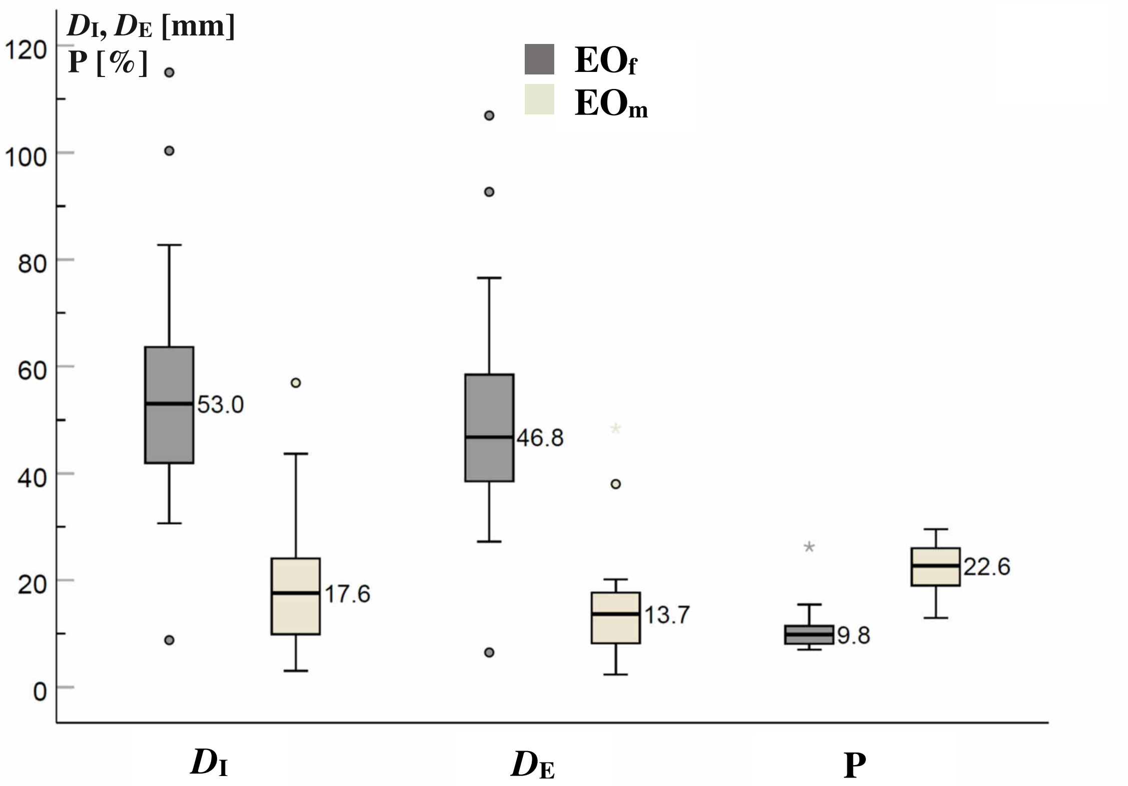


Figure 15: SAT thickness sums D_I and D_E of the eight standardised body sites.
Index I refers to including, and index E refers to excluding embedded fasciae in the SAT. Thirteen female (EO_f), and eighteen male (EO_m) elite Judokas were measured immediately before the official weigh-in for the European Open (EO) international competition in Oberwart Men, February 16-17, 2018, and Women February 15, 2019. Abbreviations: P= $100F/D_I = 100(D_I - D_E)/D_I$.

Figure 15 shows SAT thickness sums in terms of D_I and D_E (including and excluding fibres) in elite female (N=13) and male (N=18) judokas measured immediately before the official weigh-in (weigh-in: 7 to 7:30 pm) for an international competition. The median D_I value in females was 53.0 mm, and 17.6 mm in males, respectively (in other words: about 3.0 times higher in the female group). The median SAT thickness excluding fibres was 46.8 mm in females, and 13.7 mm in males. The median percentage (P) of embedded fibrous structures in the SAT was 9.8 % in females, and 22.6 % among the eighteen males. The median percentage of fibres was about 2.3 times higher in competing male judokas compared to females.

3.1.1 *Relative Body Mass (MI_1) and Subcutaneous Fat Sums (D_I) in Elite Judokas Before Competition.*

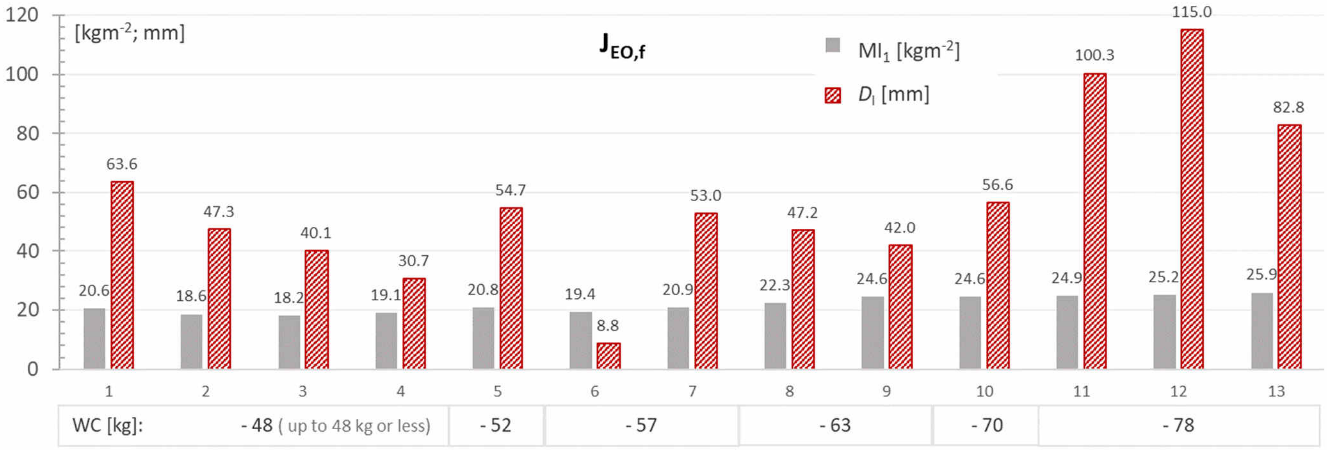


Figure 16: Relative body mass (MI_1) and subcutaneous adipose tissue in a subset of female judokas. The bar charts show the mass index (MI_1) and SAT thickness sums (D_I) of thirteen female judokas at their chosen weight category (WC). The measurements were performed on the day of the official weigh-in before the European Open (EO) Women competition in Oberwart (February 15, 2019). Abbreviations: (cn) case number, cn 1–4 (- 48 kg) extra-lightweight, cn 5 (- 52 kg) half-lightweight, cn 6–7 (- 57 kg) lightweight, cn 8–9 (- 63 kg) half-middleweight, cn 10 (- 70 kg) middleweight, cn 11–13(- 78 kg) half-heavyweight.

Figure 16 shows the relative body weight in terms of MI_1 and SAT thickness sums D_I of thirteen elite female judokas. The median MI_1, and D_I on the day before an international competition (immediately before the official weigh-in) was 20.9 kg m^{-2} (IQR 5.5), and 53.0 mm (IQR 32.1), respectively. When analysing the whole group ($J_{EO,f}$, N=13) including all WC, there was a significant positive correlation between the chosen WC and D_I ($r_s = 0.596$, $p = 0.032$), and MI_1 ($r_s = 0.947$, $p < 0.01$). The lower WCs (by excluding WC– 78 kg, N=3) show no significant correlation between WC and D_I ($r_s = 0.107$; $p = 0.769$) but a significant correlation with the MI_1 ($r_s = 0.894$, $p < 0.01$). In the male group ($J_{EO,m}$, N=17; excluding one adolescent, (cn) case number 3), there was no significant correlation between the chosen WC and D_I ($r_s = 0.347$, $p = 0.172$), but a significant correlation between WC and MI_1 ($r_s = 0.953$, $p < 0.01$) (see Figure 17). When excluding the athlete at the WC half-heavyweight (up to 100 kg or less, cn 18 in Figure 17), there was no significant correlation between WC and D_I

($r_s = 0.338$, $p = 0.200$), and for WC and MI_1 there was a significant correlation ($r_s = 0.846$, $p < 0.01$).

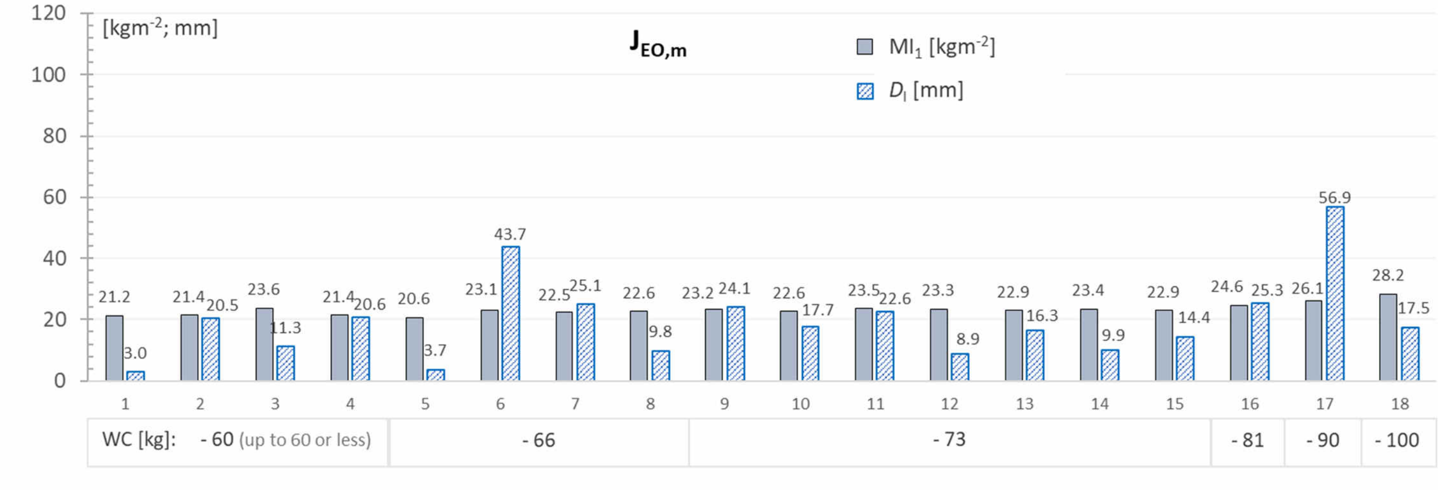


Figure 17: as in Figure 16, but for competing elite male judokas.
The measurements were performed in eighteen male judokas ($J_{EO,m}$) on the day before the official weigh-in before the European Open (EO) Men competition in Oberwart (February 16–17, 2018). Abbreviations: (cn) case number, cn 1–4 (- 60 kg) extra-lightweight, cn 5–8 (- 66 kg) half-lightweight, cn 9–15 (- 73 kg) lightweight, cn 16 (- 81 kg) half-middleweight, cn 17 (- 90 kg) middleweight, cn 18 (- 100 kg) half-heavyweight.

3.1.2 Comparative Measurements of Elite Female Judokas.

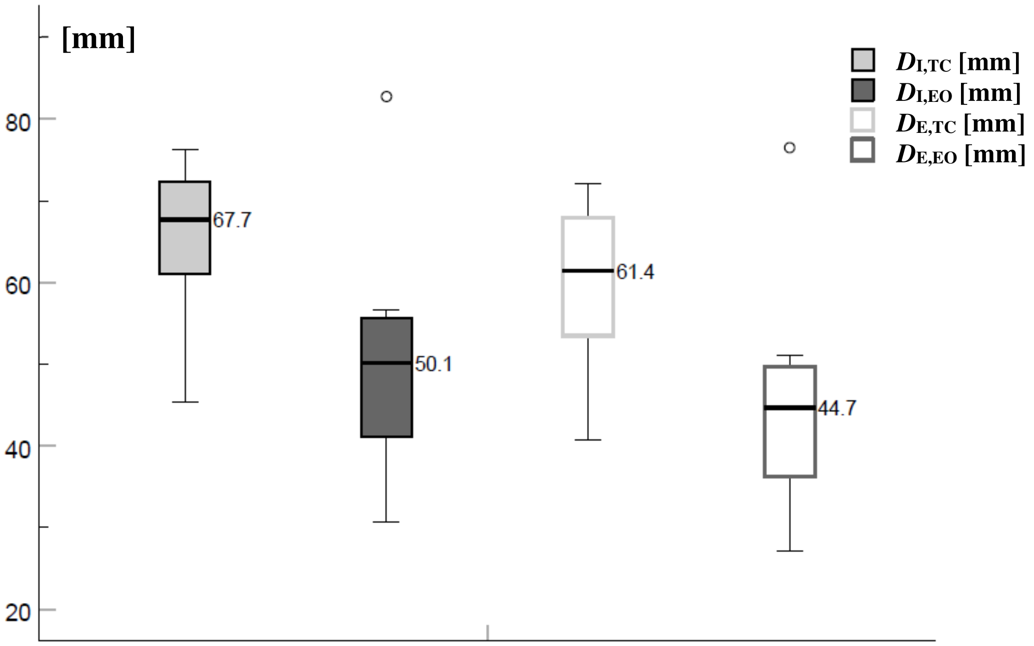


Figure 18: Comparison of subcutaneous adipose tissue (SAT) thickness sums (D_I) of a sub-group of eight female judokas at two different times.
Index I refer to including fibres, Index E refer to excluding fibres. Abbreviations: (TC) training camp (January 7–9, 2016 in Mittersill, Austria), or in-season measurements during following weeks, (EO) measurements before weigh-in (7 to 7:30 pm) for an international competition (European Open Women in Oberwart, Austria, February 15, 2019).

The boxplots in Figure 18 show the median SAT thickness sum of D_I, and D_E in a sub-group of eight female judokas at two different measurement series. US measurements were performed during an international training camp (TC) (or for two cases in the following weeks), and for a second time immediately before an official ‘weigh-in’ (on the day before an international competition), termed EO. The D values (both, included (I) or excluded (E) fibres) significantly differed: D_I (t (7) = 2.733, p=0.029); D_E (t (7) = 2.604, p=0.035) between TC and EO.

Table 13: Comparative measurements: anthropometry and fat patterning of a sub-group of eight female elite judokas measured at two time points.

VARIABLE [UNIT]	**$J_{f,TC}$** MEAN (±SD)	**$J_{f,EO}$** MEAN (±SD)	**test results**
m [kg]	62.5* (8.5)	59.6* (10.6)	**t (7) = 2.957, p=0.021**
BMI [kgm^{-2}]	23.3* (1.9)	22.2* (2.5)	**t (7) = 3.034, p=0.019**
MI$_I$ [kgm^{-2}]	23.1* (2.2)	22.1* (2.8)	**t (7) = 2.988, p=0.020**
w [m]	0.689* (0.046)	0.672* (0.059)	t (7) = 1.644, p=0.144
g [m]	0.949* (0.045)	0.927* (0.059)	**t (7) = 2.761, p=0.028**
b [m]	0.308* (0.021)	0.306 (0.025)	Z = -1.187, p=0.235
t [m]	0.503* (0.030)	0.488* (0.043)	t (7) = 2.077, p=0.076
W=w/h [1]	0.422 (0.023)	0.411* (0.027)	t (7) = 1.640, p=0.145
SAT THICKNESS SUMS D_I and D_E [mm]; MEDIAN (IQR)			
D_I	67.7* (14.0)	50.1* (15.5)	**t (7) = 2.733, p=0.029**
D_E	61.4* (17.4)	44.7* (15.3)	**t (7) = 2.604, p=0.035**
SAT THICKNESSES AT INDIVIDUAL BODY SITES d_I [mm]; MEDIAN (IQR)			
$d_{I,UA}$	4.7* (3.3)	3.2* (2.7)	t (7) = 2.082, p=0.076
$d_{I,LA}$	10.6* (7.6)	6.4* (2.8)	**t (7) = 1.900, p=0.099**
$d_{I,FT}$	8.5* (1.7)	7.1* (2.5)	t (7) = 2.316, p=0.054
$d_{I,LT}$	21.5* (7.6)	15.7* (5.0)	**t (7) = 3.111, p=0.017**
$d_{I,MC}$	4.8* (2.3)	4.6* (2.9)	t (7) = 1.716, p=0.130
$d_{I,ES}$	5.7* (2.6)	4.9* (2.7)	t (7) = 1.215, p=0.264
$d_{I,DT}$	7.0* (2.9)	5.9* (4.0)	**t (7) = 3.420, p=0.011**
$d_{I,BR}$	1.9* (1.3)	1.4* (2.1)	t (7) = 1.249, p=0.252

Asterisks (*) mark normally-distributed data where the paired t-test (t) was used. The Wilcoxon test (Z) was used for not normally-distributed data. Significant results are in bold. Abbreviations: (TC) training camp (January 7–9, 2016 in Mittersill, Austria), or in-season measurements during following weeks, (EO) European Open (February 15, 2019 in Oberwart, Austria); body mass (m), body mass index (BMI= $\frac{m}{h^2}$), mass index (MI$_I$= $0.53 \cdot m/(hs)$); 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.

The variation in selected anthropometric variables and fat patterning of the standardised eight body sites between two measurements is shown in Table 13. Significant differences between TC and EO were measured at m (t (7) = 2.957, p=0.021), BMI (t (7) = 3.034, p=0.019), MI_1 (t (7) = 2.988, p=0.020), g (t (7) = 2.761, p=0.028), LA (t (7) = 1.900, p=0.099), LT (t (7) = 3.111, p=0.017), and DT (t (7) = 3.420, p=0.011).

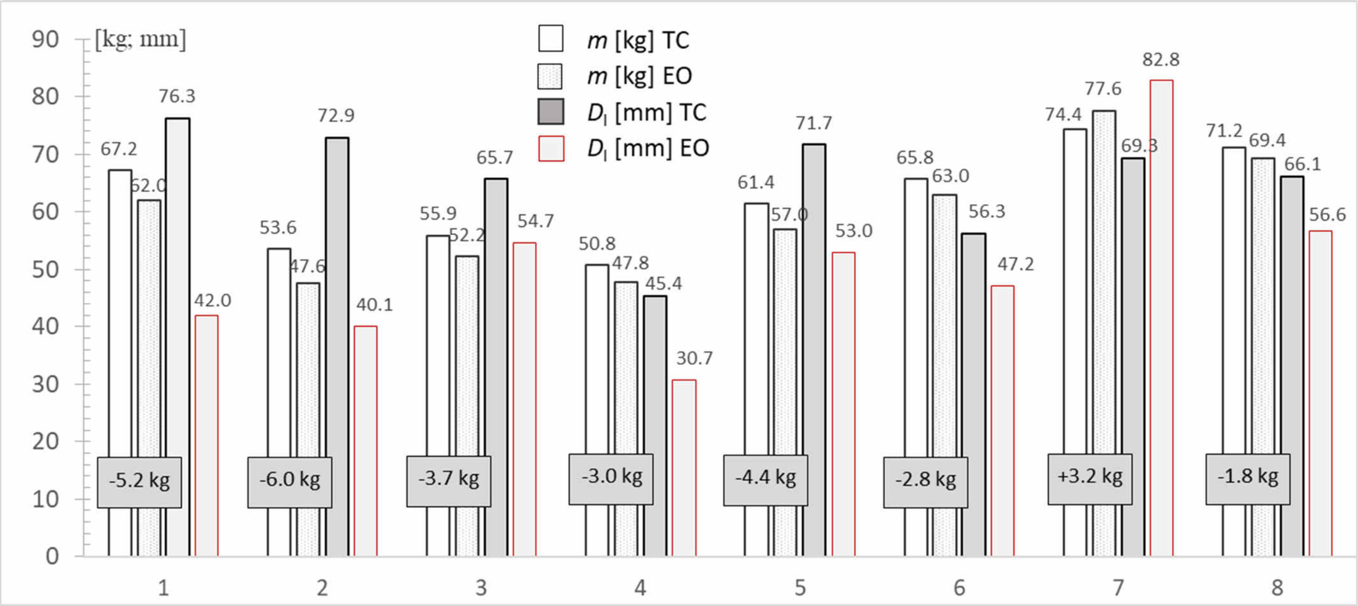


Figure 19: Changes of body mass (m) and subcutaneous fat (SAT) thickness sums (D_I) in a sub-group of eight elite female judokas.
Abbreviations: (TC) training camp (January 7–9, 2016 in Mittersill, Austria), or in-season measurements during following weeks, (EO) European Open (February 15, 2019 in Oberwart, Austria). Note: changes of the weight category (WC) over time: case number (cn) 2, and 7.

Figure 19 shows the differences in body mass (m) and D_I of eight female judokas at two measurement series. The athletes were measured while an international training camp (in 2016), and at a second time point immediately before the official ‘weigh-in’ as preparation for an international competition (European Open Women in Oberwart, Austria, 2019). Two females (cn 2 and 7 in Figure 19) changed their weight category (WC) over time. Cn 2 changed from WC up to 52 kg or less to WC up to 48 kg or less and had to reduce her body mass by 6 kg. Cn 7 (in Figure 19) changed from WC up to 70 kg or less to WC up to 78 kg or less and increased her body mass by 3.2 kg. The mean weight loss of the six remaining judokas between these two measurements was 3.5 kg ±1.1 kg (i.e., 5.7 % ± 1.7 % of body mass). The highest value was 5.2 kg (7.7 %), and one case of 4.4 kg (7.2 %).

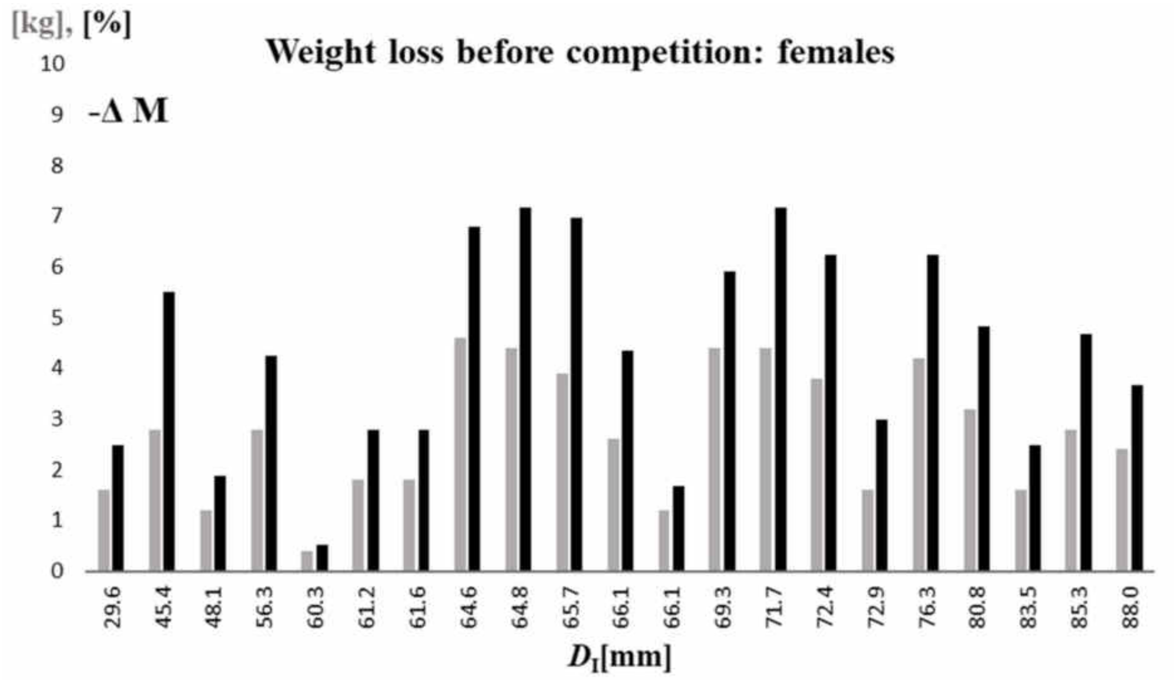


Figure 20: Weight loss before competition in female judokas (Sengeis et al., 2019 (58)). Grey columns represent the weight loss before competition in all females (except for heavy weight category), and black columns represent the weight loss in percent of body mass. Athletes are ordered according to their sums of SAT thicknesses D_I. Reproduced from "Body weight and subcutaneous fat patterning in elite judokas", Sengeis M, Müller W, Störchle P et al. Scand J Med Sci Sports 2019;00:1–15; with permission from John Wiley & Sons, Inc.

Figure 20 and Figure 21 show comparisons between the body weights measured during the research study (Mittersill 2016 and following weeks) with the maximum allowed body weight of the athletes' chosen weight category limits (see Figure 20, and Figure 21). *"In the training phase when measurements took place, most judokas (except for the five heavy weight athletes and another six) had body masses above their weight category limits: the mean (N=50) was 3.0 kg ±1.4 kg (i.e., 4.3% ± 2.0% of body mass), the highest values were 7.4 kg (9.2%), two cases with 4.9 kg (6.9% and 6.3%), and four cases with 4.6 kg (7.7%, 6.8%, 5.4%, and 5.4%). Mean weight loss of females (N=21) was 2.7 kg ±1.3 kg (4.4% ± 2.0%), and of males (N=29) 3.3 kg ±1.4 kg (4.3 % ± 2.0%). There was no significant correlation between weight losses and sums of SAT thicknesses (females: ρ=0.26, p=0.25; males: ρ=0.19, p=0.34), and there was also no significant correlation between weight losses and SAT thicknesses measured at the UA and LA site (UA: females: ρ=-0.08, p=0.73; males: ρ=-0.003, p=0.99); LA: females: ρ=0.24, p=0.30; males: ρ=0.01, p=0.97). The mean weight losses in athletes measured in the same training period (January 7-9, 2016) (N=40) was: 3.0 kg ±1.3 kg (i.e. 4.2% ± 1.9% of body mass), and there was also no significant correlation* *between weight losses and SAT thicknesses (females: ρ=0.21, p=0.42; males: ρ=0.34, p=0.12) in both sexes"*(58).

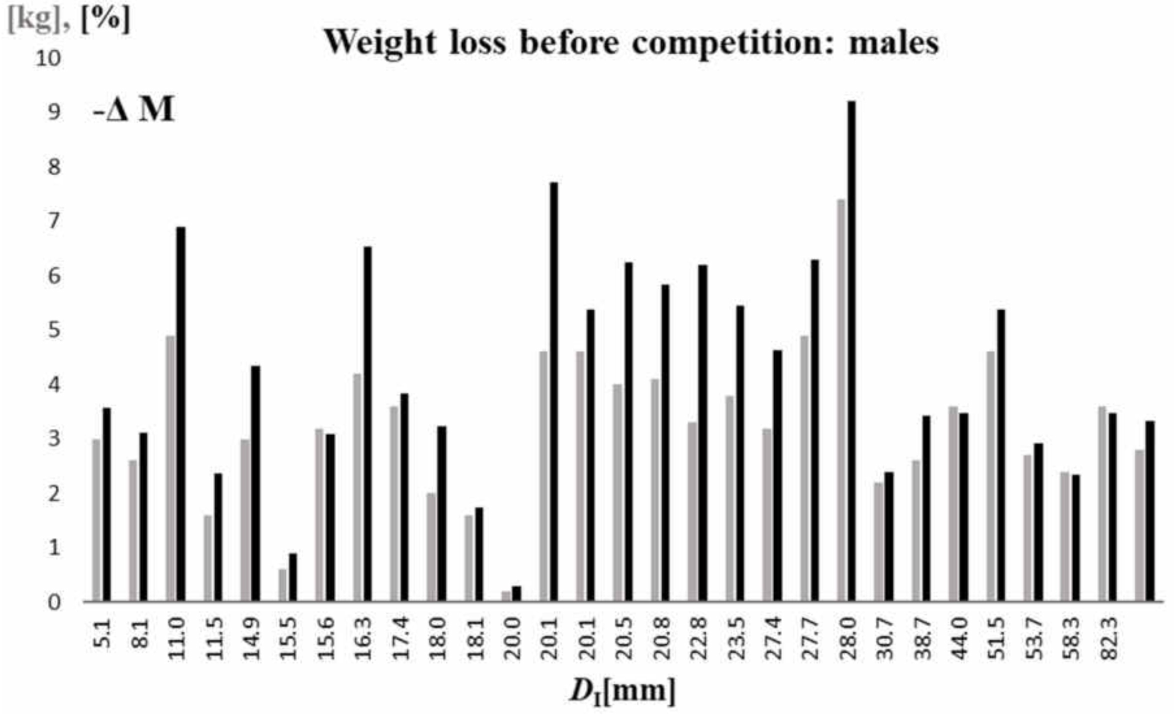


Figure 21: As Figure 20, but for males (Sengeis et al., 2019 (58)).
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SECTION 2: Application of the B-Mode US Method in Kenyan long-distance runners.

Results obtained were published in the Int J Sports Med 2020. Core parts of the publication are cited literally. Numbers of figures and tables were modified to fit to this thesis structure.

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3.2 Relative Body Weight and Fat using US in elite Kenyan long-distance runners.

Table 14 shows mean values (± SD, minimum and maximum) of age, body height, body mass as well as length, circumference, and calculated indices.

Table 14: Descriptive statistics of the Kenyan elite female (K_f) and male (K_m) long-distance runners (Sengeis et al., 2020 (106)).

		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
MI_1	[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/h^2*), mass index (*$MI_1 = 0.53 \cdot m/(hs)$*), Cormic index (C=s/h), waist girth (w), gluteal (110) girth (g), biceps girth flexed and tensed (b), thigh girth at the site front thigh (t), waist-to-height 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".*

Adapted from Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

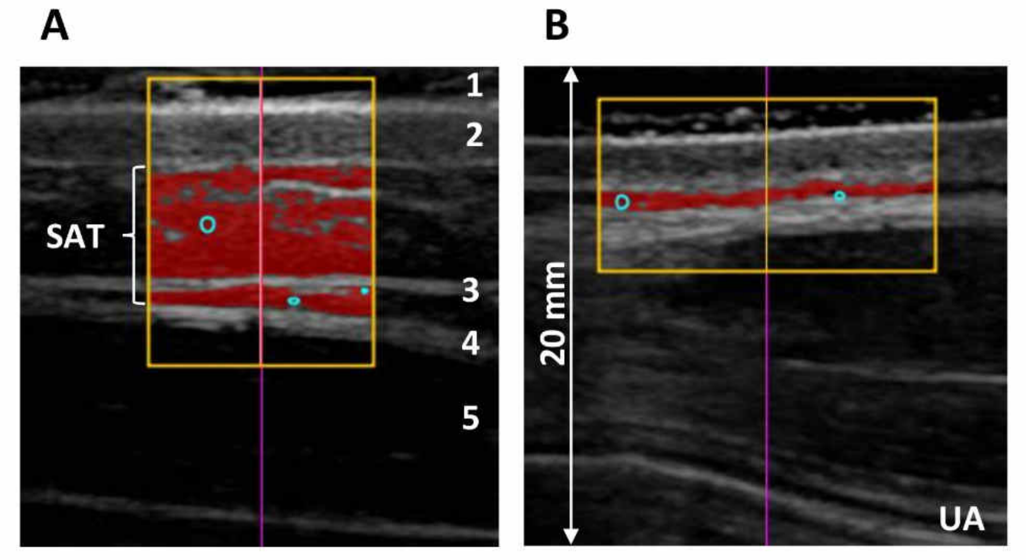


Figure 22: Exemplarily-chosen images of two male long-distance runners.
Athletes had similar body mass indexes (BMI), but enormous differences in subcutaneous thickness sums (D_I). Reproduced from (106) "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

Figure 22 A and B show two evaluated US images of two elite male long- distance runners. Both athletes (**A:** BMI = 19.0 kg m^{-2}, MI_1 = 19.4 kg m^{-2}, D_I = 20.2 mm, ΔWR [%] 10 km = 10.2 %, personal best (PB) time (10k) = 00:28:59, ΔWR [%] half marathon (HM) = 7.6 %, PB for HM = 01:02:45, and **B:** BMI = 18.7 kg m^{-2}, MI_1 = 19.8 kg m^{-2}, D_I = 6.0 mm, ΔWR [%] marathon (M) = 11.2 %, personal best (PB) time (M) = 02:15:18) had similar BMIs, but huge differences (240%) in D_I values (106). Figure 22 A and B show the SAT thickness at the body site upper abdomen (athlete from image A had: $d_{I,UA}$ = 5.4 mm; and athlete from image B had: $d_{I,UA}$ = 0.53 mm).

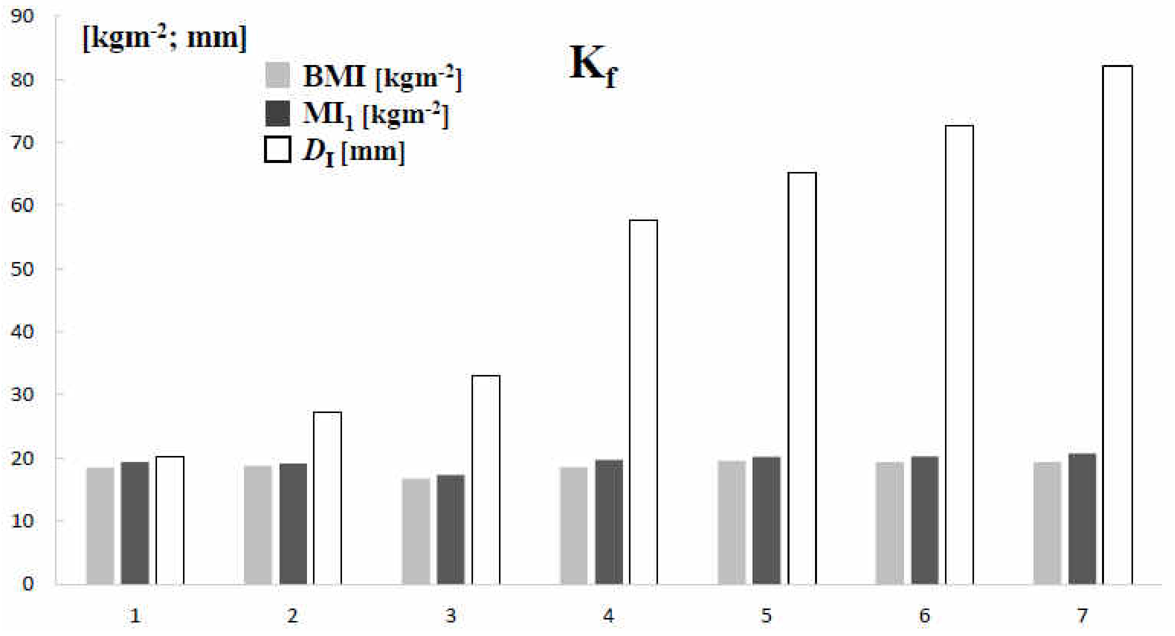


Figure 23: Body mass index (BMI), mass index (MI_1) and subcutaneous adipose tissue (SAT) thickness sums (D_I) in female Kenyan (K_f) runners (Sengeis et al., 2020 (106)).
"The columns represent BMI, the MI_1, and the SAT thickness sums (D_I) of the eight standardised measurement sites. The index I refers 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 ($r = 0.728$, $p=0.063$)". Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

Figure 23 and Figure 24 show the BMI and the MI_1 of seven international-competing female (best 10 000 m time: 32:17 min., best half marathon (HM) time: 01.11:20), and 25 male (best 10k time 28:19 min., best HM time 01:02:32, best marathon time: 02:12:00) Kenyan long-distance runners. The columns are ordered according to increasing D_I. *"All athletes (N=32) had higher MI_1 than BMI values, indicating their longer legs when compared to groups of White Caucasians (111, 112). 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 MI_1 ($r_s = 0.340$, $p=0.096$)"(106).*

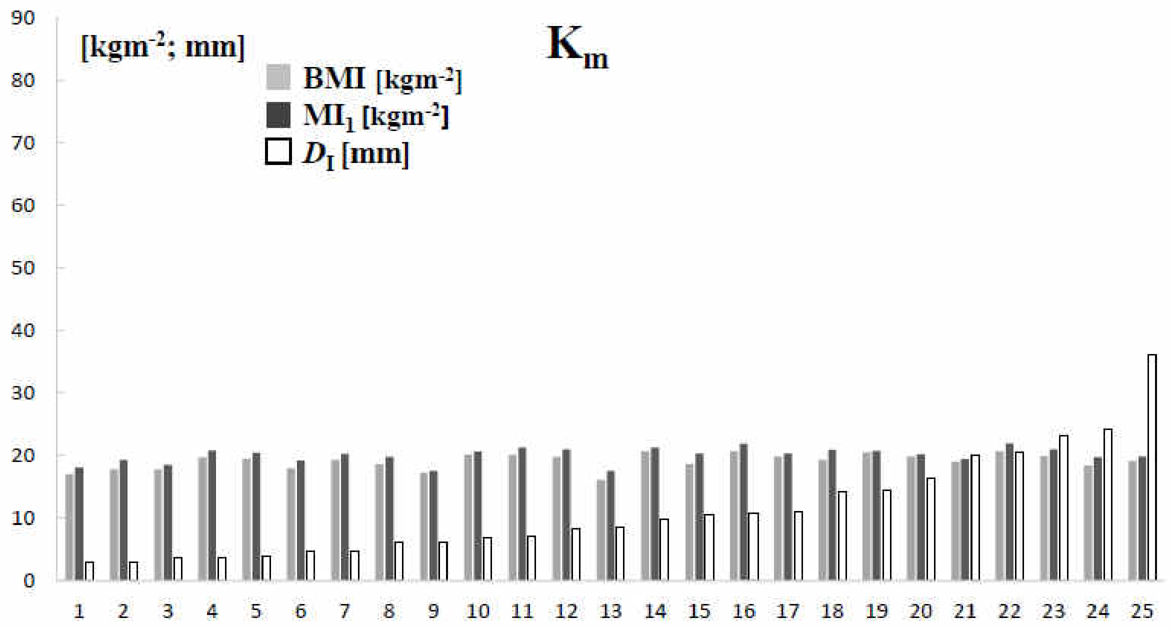


Figure 24: as in Figure 23, but for male Kenyan log-distance runners (K_m) (Sengeis et al., 2020 (106)).
"There was a moderate correlation between D_I and BMI ($r_s = 0.427$, $p=0.033$), but not between D_I and MI_1 ($r_s = 0.340$, $p=0.096$)". Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

According to the World Health Organization (WHO (54)) the 'underweight' cut-off line is defined by BMI 18.5 kg m^{-2}. This defined border is marked as a red line in Figure 25 and Figure 26. *"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* (Figure 26)*, 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)"(106).*

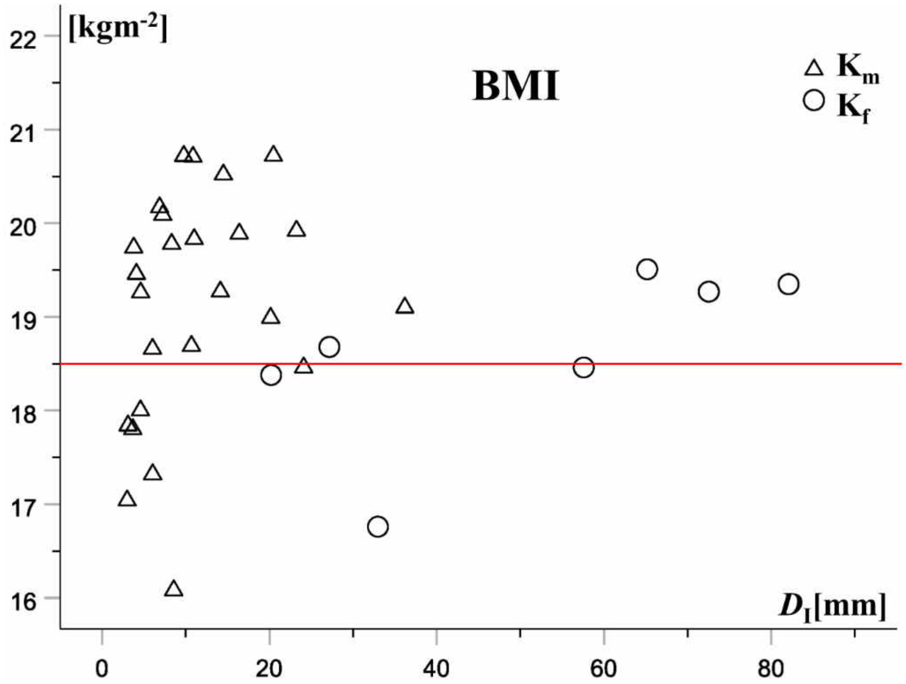


Figure 25: Underweight in terms of Body Mass Index (BMI) and Mass Index (MI_1) (Sengeis et al., 2020 (106)).

“The ‘underweight’ cut-off line (BMI = 18.5 kgm^{-2}; according to the WHO (54)) 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_I) 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_I: sum of the eight standardised sites with fibrous structures included. Reproduced from “Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat”, Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

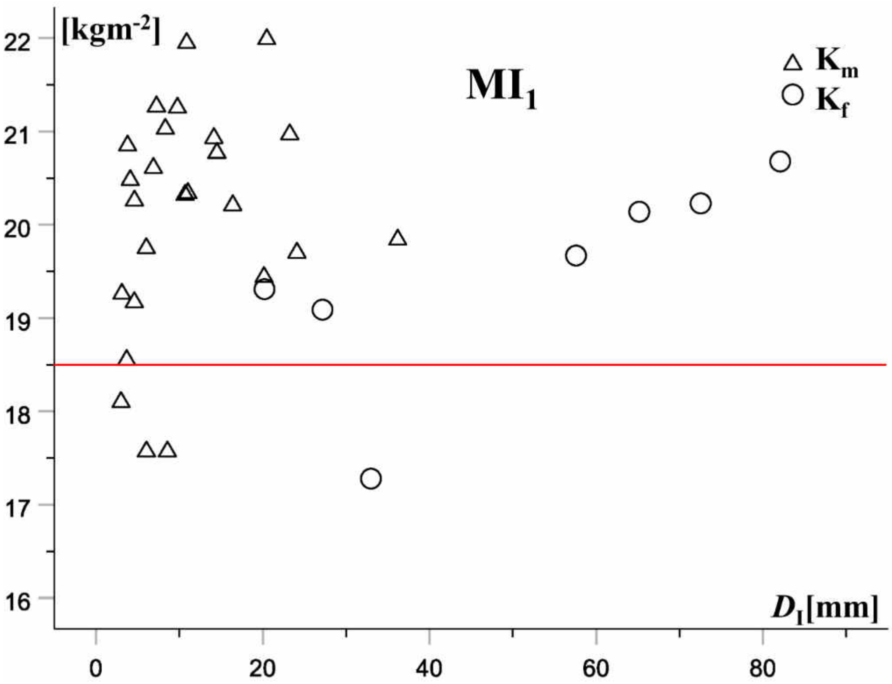


Figure 26: Underweight in terms of Mass Index (MI$_1$) (Sengeis et al., 2020 (106)).

“As in Figure 25, *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’ (54)”.*
Reproduced from “Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat”, Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

“The differences MI$_1$ - BMI are shown in Figure 27*; they ranged from 0.4 kgm^{-2} to 1.3 kgm^{-2} in females (bright grey columns) and from 0.3 to 1.7 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})”(106).*

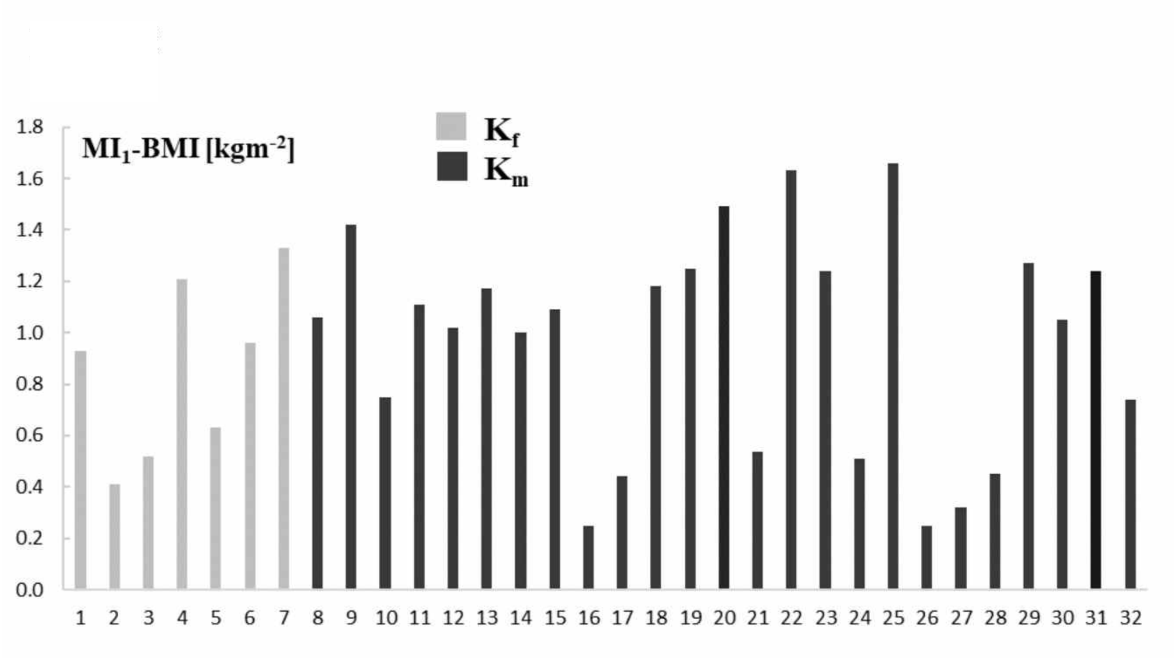


Figure 27: Differences between MI_1 and BMI in Kenyan Long-Distance-Runners (Sengeis et al., 2020 (106)).
"All MI_1 values were higher than the according BMI values. Differences in the group (K_f) ranged from 0.4 to 1.3 kg m^{-2}, and in the male group (K_m) from 0.3 to 1.7 kg m^{-2}. MI_1 and BMI differed significantly (t (30)=-13.073, $p<0.01$)". Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

Figure 28 and Figure 29 *"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. For the case that 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"(106).*

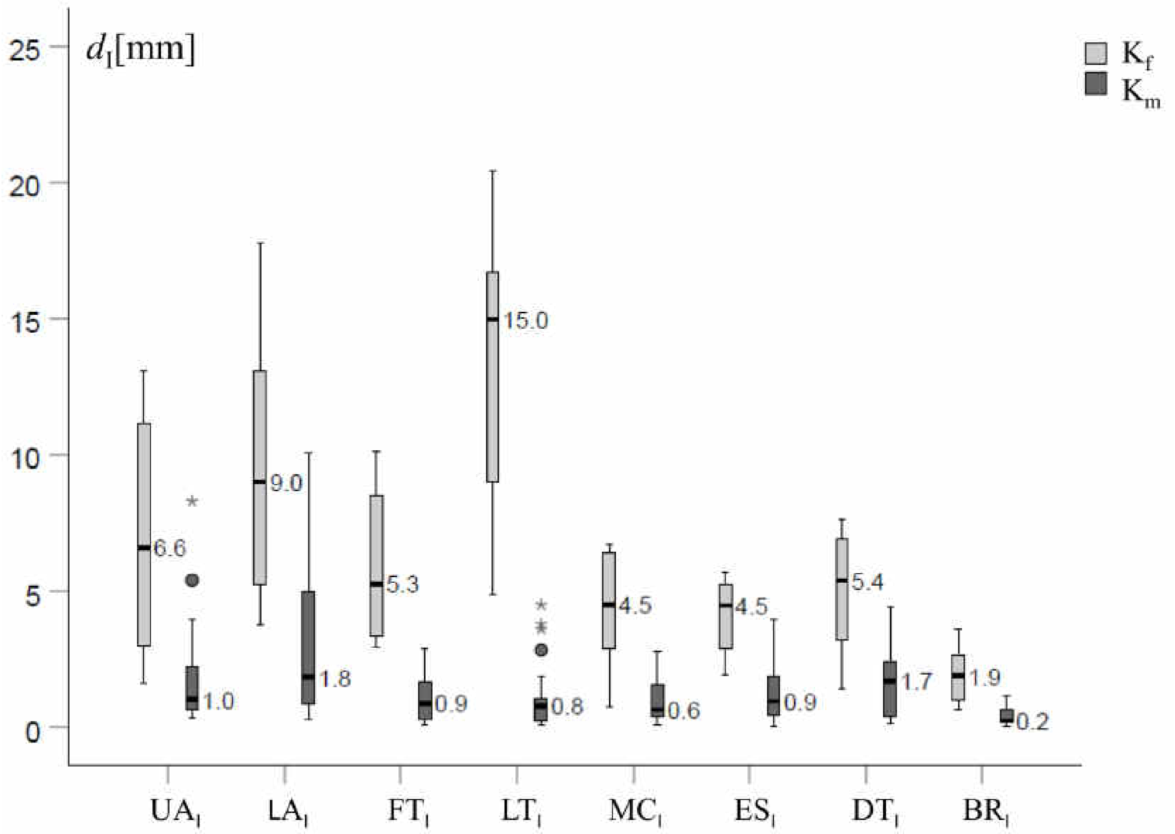


Figure 28: Subcutaneous adipose tissue (SAT) patterning in female and male Kenyan runners (Sengeis et al. (106)).
"SAT thickness patterning (d_I) at the eight standardised body sites including embedded fibrous structures (index I) in female (K_f) and in male (K_m) long-distance runners. All eight standardised 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)".
Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

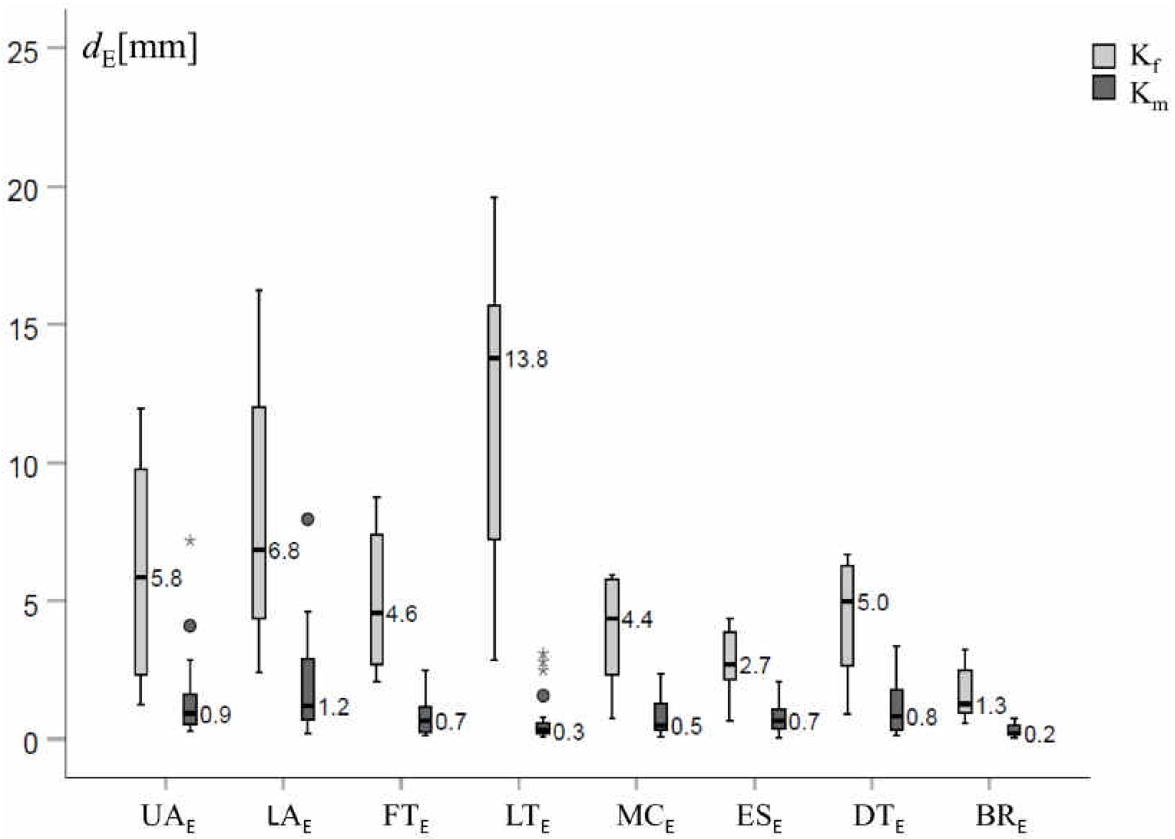


Figure 29: as in Figure 28, but excluding embedded fibrous structures in the SAT measurements (d_E) (Sengeis et al., 2020 (106)).

"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)". Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

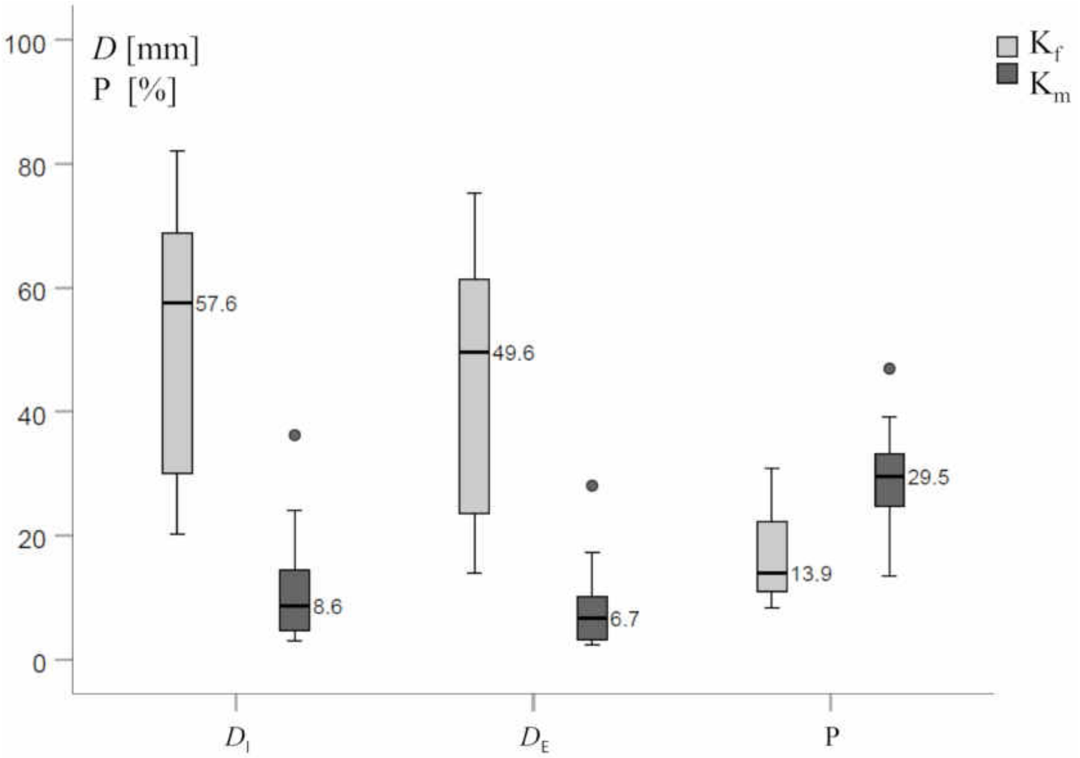


Figure 30: Subcutaneous adipose tissue (SAT) thickness sums D_I and D_E (Sengeis et al., 2020 (106)). *"SAT thickness sums D_I in females and males. Percentages (P) of fibrous structures (F) embedded in the SAT are also shown: $P = 100F/D_I = 100(D_I\text{-}D_E)/D_I$. There were significant differences 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)"*. Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

Figure 30 *"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"*(106).

Figure 31 and Figure 32 show dependencies of performances in 10-kilometer, half marathon, and marathon distances on SAT thickness sums in terms of D_I for the female (K_f; N=7) and male (K_m; N=25) groups. In the male sub-group of nineteen athletes with a performance level better than the world record (WR) plus 15 %, higher body fat values were not associated with higher running performance (ΔWR), given in terms of percentual differences compared with the WR. There was a (weak) negative correlation between body fat in terms of D_I and ΔWR (r_s = -0.390, p = 0.033). As a reference in Figure 31 to Figure 34, the 10-kilometer

(10k) WR (until September 2019) for females was 29:17:45, and for males 26:17:54. For the half marathon (HM) distance (21.0975 km) the WR for females was 1:04:51 and for males 58:01. For the marathon (M) distance (42.195 km), the WR for females was 2:15:25 (Birgit Kosgei, Chicago 2019 (113)), and for males 2:01:39 (Eliud Kipchoge, Berlin 2018 (113)). *"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 ($r = 0.782$, $p=0.002$)"*(106).

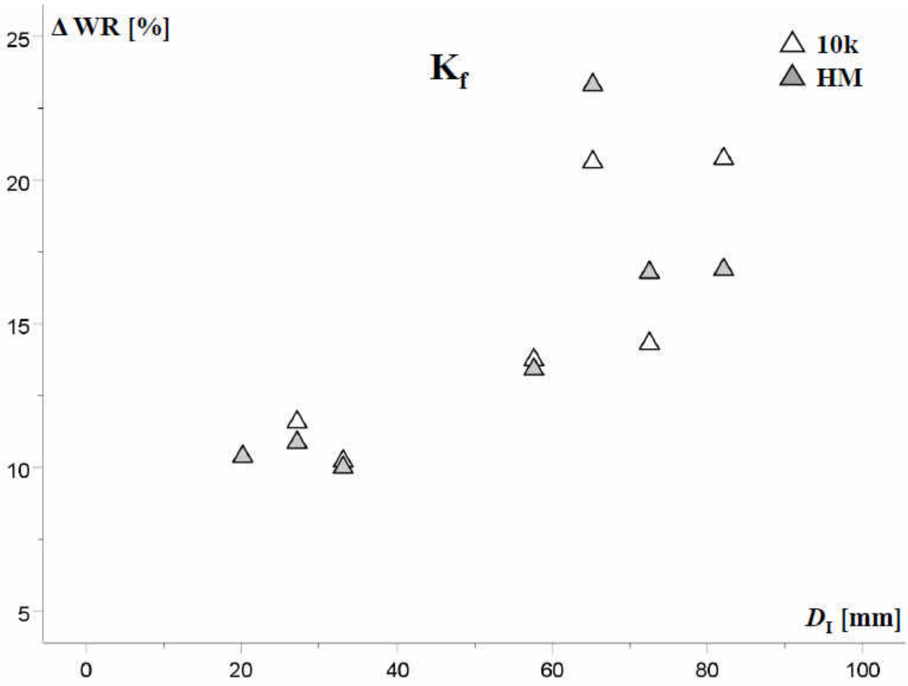


Figure 31: Dependency of running performance on body fat (D_I) (Sengeis et al., 2020 (106)). *"The dependencies of performances on subcutaneous adipose tissue thickness sums (D_I) and on relative body weight (MI_I)* (Figure 33, and Figure 34) *are shown for the female (K_f; N=7) and male (K_m; N=25) 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 [%] $=100 \cdot (PB - WR)/WR$. 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".* Figure 31: *"Female group Kf: There was a significant positive correlation between D_I 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 sub-group with personal best times below or close to world record time plus 10%, there was no correlation".* Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

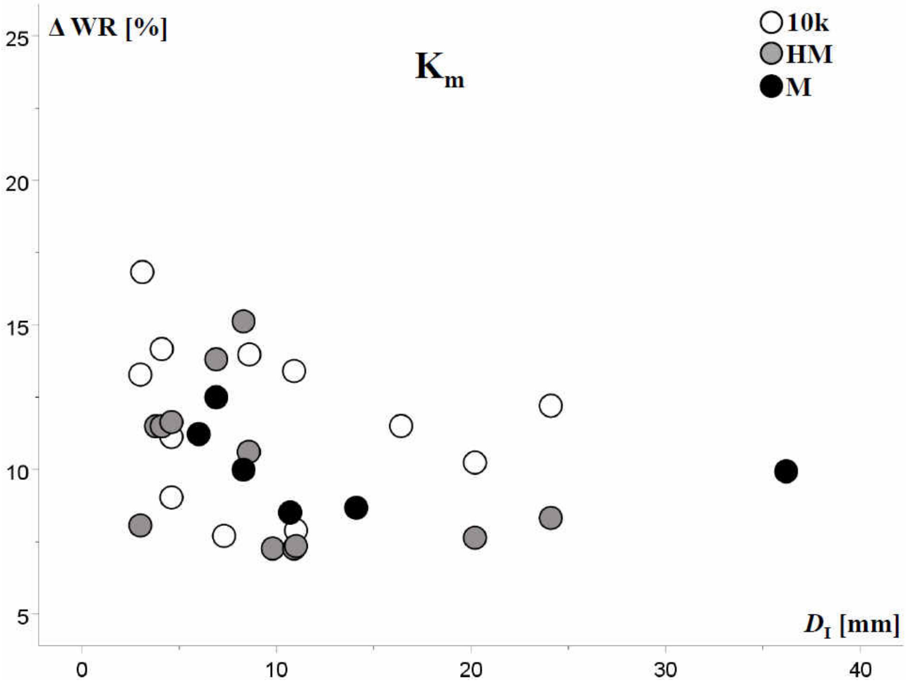


Figure 32: as in Figure 31, but for the male group (K_m) (Sengeis et al., 2020 (106)).
“There was a (very) weak negative correlation between D_I and running performance in K_m ($r_s = -0.390$, $p=0.033$)”. Reproduced from “Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat”, Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

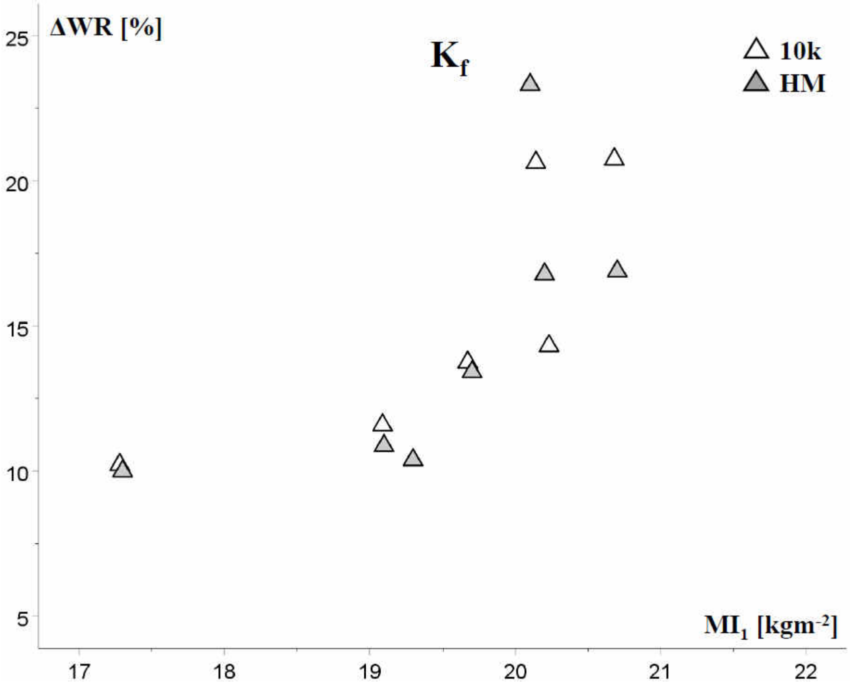


Figure 33: Running performance and relative body weight (MI_1) in the female group (K_f) (Sengeis et al., 2020 (106)).
There was a significant correlation between ΔWR [%] and MI_1($r_s = 0.835$, $p<0.001$). *“However, the PB times show that there was a larger performance range in the female group compared to the male group. In the sub-group with PB times below or close to WR time plus 10% (N=3), there was no*

correlation". Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

Figure 33, and Figure 34 use the relative body weight in terms of MI_1 instead of D_I (Figure 31, and Figure 32). In female Kenyan long-distance runners (K_f; N=7), there was a significant positive correlation between running performance and MI_1 ($r_s = 0.835$, $p < 0.001$). Using BMI – as a commonly-used value for relative body weight – resulted in analogous findings. Although this study was well designed, the small number of females should be interpreted carefully.

In Figure 34, running performance and the relative body weight M_I were shown in the male group (K_m). There was no significant correlation (N=19, sub-group with performance level better than WR plus 15 %) between running performance and MI_1 ($r_s = -0.152$, $p = 0.424$).

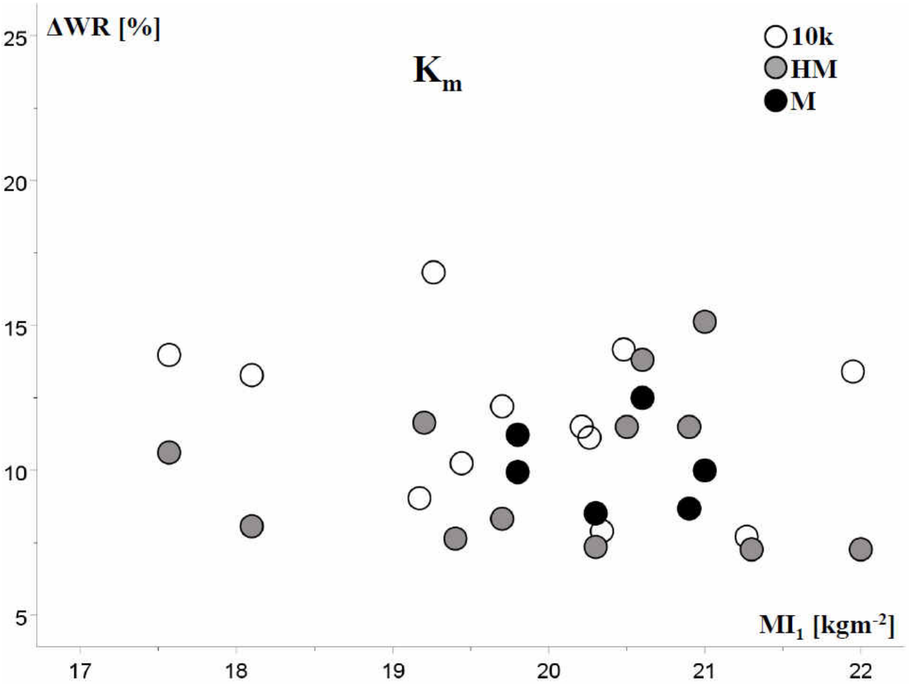


Figure 34: as in Figure 33, but for the male group (K_m) (Sengeis et al., 2020 (106)). There was no significant correlation between ΔWR [%] and MI_1 [kg m^{-2}] ($r_s = -0.152$, p=0.424). Reproduced from "Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat", Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

In Table 15, comparisons of two measurement series E1 (in Kenya) and E2 (in Austria, 18 weeks later) including a sub-group of nine male athletes were performed. *"There were no statistically significant differences (p>0.05) between E1 and E2 concerning the variables*

BMI, MI_I, D_I, and D_E. At the individual eight sites, the SAT thicknesses (d_I) also did not differ significantly”(106).

Table 15: Comparison of a sub-group of nine runners who were measured in Kenya (E1) and in Austria 18 weeks later (E2) (Sengeis et al., 2020 (106)).

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$_I$ [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/h^2*), mass index (MI$_I$=* $0.53 \cdot m/(hs)$*), sum of the eight standardised subcutaneous adipose tissue (SAT) sites* ***i****ncluded (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.* Adapted from “Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat”, Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Int J Sports Med. 2020 Oct 14. doi: 10.1055/a-1268-8339. Epub ahead of print. PMID: 33053598; with permission from © Georg Thieme Verlag KG.

SECTION 3: Application of the standardised US Method in Elite Athletes in Different Sports.

3.3 Differences of SAT Thicknesses and Fat Patterning Between Female and Male Elite Athletes in Different Sports.

Descriptive statistics of all included elite athletes (N=272, 39% females, and 61% males) separated by sex and eleven different sports, their age, body height (h), sitting height (s), leg length (l), body mass (m), and relative body weights in terms of body mass index (BMI = $\frac{m}{h^2}$), and the improved mass index ($\text{MI1} = 0.53 \cdot m/(hs)$) are shown in Table 16.

Table 16: Descriptive statistics of the athlete groups: body lengths, body mass, and relative body weights in terms of BMI, and mass index (MI_1).

SPORTS	**sex**	**n**	**age**	***h***	***s***	***l***	***m***	**BMI**	**MI_1**
MEAN (±SD)			[years]	[m]			[kg]	[kg m^{-2}]	
Athletics(a,b)	*f*	*7*	*24.1* (5.6)*	*1.647* (0.065)*	*0.835 (0.037)*	*0.954 (0.040)*	*50.5* (2.6)*	*18.6* (0.9)*	*19.5* (1.1)*
	m	*25*	*27.2* (3.3)*	*1.680* (0.058)*	*0.847* (0.026)*	*0.963* (0.044)*	*54.0* (4.3)*	*19.1* (1.2)*	*20.1* (1.2)*
Badminton	f	3	21.0* (3.6)	1.673* (0.070)	0.901* (0.015)	0.918 (0.056)	65.8* (6.0)	23.6* (3.6)	23.2* (3.1)
	m	12	22.5* (4.3)	1.803* (0.069)	0.946* (0.044)	1.010* (0.037)	71.8* (9.0)	22.0* (1.6)	22.2* (1.7)
Boxing	f	2	25.0 (5.7)	1.636 (0.037)	0.880 (0.012)	0.893* (0.036)	59.2 (0.8)	22.1 (1.3)	21.8 (1.1)
	m	10	21.0 (3.4)	1.797* (0.090)	0.939* (0.035)	0.997* (0.065)	78.0* (15.6)	24.0* (3.2)	24.3* (3.4)
Hockey	f	30	22.5* (3.0)	1.658* (0.060)	0.889* (0.025)	0.906* (0.046)	63.5* (5.9)	23.1* (1.8)	22.9* (1.8)
	m	28	23.6* (3.6)	1.818* (0.065)	0.966* (0.038)	1.000* (0.043)	79.6* (9.1)	24.0* (1.9)	23.9* (2.1)
Judo(c)	f	23	22.5 (5.0)	1.681* (0.069)	0.896* (0.036)	0.936* (0.042)	65.2 (8.9)	23.0* (2.2)	22.9* (2.2)
	m	41	24.1 (5.0)	1.768* (0.073)	0.939* (0.037)	0.980* (0.053)	81.2 (17.2)	25.8 (3.8)	25.7 (3.8)
Orienteering	f	6	23.2 (2.5)	1.649* (0.052)	0.885* (0.019)	0.892* (0.026)	56.8* (5.0)	20.9* (0.7)	20.6* (0.9)
	m	11	21.6 (3.7)	1.809* (0.045)	0.943* (0.022)	1.019* (0.042)	69.6* (4.4)	21.3* (1.7)	21.6* (1.5)
Shooting(d)	f	1							
	m	7	33.4* (12.8)	1.814 (0.045)	0.956* (0.020)	0.998 (0.047)	84.3* (11.1)	25.6* (3.0)	25.8* (3.5)
Taekwondo	f	4	23.0* (1.8)	1.731* (0.095)	0.928* (0.045)	0.931* (0.071)	63.0 (12.7)	20.9* (2.3)	20.7* (2.3)
	m	5	21.4* (2.9)	1.750* (0.110)	0.934* (0.028)	0.958* (0.099)	70.2* (10.1)	22.8* (0.9)	22.6* (1.2)
Triathlon	f	5	23.2* (3.6)	1.676* (0.063)	0.883* (0.029)	0.924* (0.049)	55.9* (4.7)	19.9 (1.3)	19.8 (1.1)
	m	10	21.9 (4.1)	1.800* (0.044)	0.953* (0.021)	1.000* (0.042)	70.7* (3.8)	21.8* (0.5)	21.8 (0.7)
Ultimate Frisbee	f	15	26.5* (3.6)	1.716* (0.068)	0.910* (0.032)	0.948* (0.044)	65.2* (6.9)	22.1* (2.0)	22.1* (1.9)
	m	9	27.3* (3.5)	1.828* (0.054)	0.964* (0.028)	1.026* (0.036)	77.0* (5.2)	23.0* (0.9)	23.2* (1.1)
Volleyball (Beach)	f	9	20.2 (2.1)	1.764* (0.064)	0.916* (0.026)	1.001* (0.048)	66.3* (6.1)	21.4* (2.4)	21.8* (2.3)
	m	9	22.1 (2.7)	1.926* (0.055)	0.995* (0.027)	1.089* (0.050)	86.2* (5.8)	23.2* (0.9)	23.8* (1.0)
Sum	f	105	23.3 (4.5)	1.683* (0.071)	0.893* (0.035)	0.932* (0.052)	62.3* (8.0)	22.1* (2.3)	22.1* (2.1)
	m	167	24.2 (5.3)	1.786* (0.084)	0.937 (0.050)	0.997* (0.055)	74.5* (14.5)	23.2 (3.3)	23.4 (3.2)

Asterisks (*) mark normally-distributed data. Abbreviations: body height (stature) h, sitting height (s), leg length (l), body mass (m), body mass index (BMI= m/h^2), mass index (MI_1= $0.53m/(hs)$). (a)Kenyan long-distance runners, (b)SAT data was published in the Int J Sports Med, 2020 (106), (c)parts published in the Scan J Med Sci Sports, 2019 (58), (d)Archery, trap, skeet.

Table 17: Selected body dimensions (circumferences, and indices) of the athlete groups.

SPORTS	**sex**	**n**	***w***	***g***	***b***	***t***	**W=*w* /*h***	**L=*l* /*h***
MEAN (±SD)			**[m]**	**[m]**	**[m]**	**[m]**	**[1]**	**[1]**
Athletics(a,d)	f	7	0.633*(0.018)	0.863*(0.027)	0.238*(0.009)	0.436*(0.017)	0.385 (0.017)	0.579*(0.011)
	m	25	0.669*(0.028)	0.835*(0.030)	0.259*(0.014)	0.441*(0.023)	0.398*(0.020)	0.573*(0.011)
Badminton	f	3	0.716*(0.056)	0.993*(0.049)	0.290 (0.030)	0.543*(0.049)	0.430*(0.048)	0.549*(0.010)
	m	12	0.750*(0.044)	0.962*(0.062)	0.310*(0.019)	0.515*(0.036)	0.416 (0.018)	0.560 (0.012)
Boxing	f	2	0.687 (0.041)	0.947 (0.028)	0.293 (0.018)	0.498 (0.031)	0.420 (0.035)	0.545*(0.010)
	m	10	0.798*(0.883)	0.953*(0.067)	0.343*(0.031)	0.518*(0.054)	0.444 (0.043)	0.555 (0.008)
Hockey	f	30	0.709 (0.059)	0.995*(0.042)	0.281*(0.016)	0.516*(0.025)	0.428 (0.036)	0.548*(0.013)
	m	28	0.783*(0.050)	0.987*(0.046)	0.327*(0.025)	0.537*(0.033)	0.431 (0.026)	0.550 (0.012)
Judo	f	23	0.698*(0.044)	0.967*(0.063)	0.309*(0.020)	0.502*(0.038)	0.414*(0.022)	0.557*(0.011)
	m	41	0.788*(0.700)	0.968 (0.072)	0.364*(0.034)	0.539 (0.051)	0.448 (0.032)	0.555 (0.013)
Orienteering	f	6	0.655*(0.030)	0.929*(0.029)	0.270*(0.012)	0.486*(0.023)	0.397*(0.017)	0.547*(0.010)
	m	11	0.731*(0.029)	0.925*(0.025)	0.294 (0.016)	0.493*(0.032)	0.404 (0.020)	0.563 (0.013)
Shooting^{b}	f	1						
	m	7	0.884*(0.116)	1.003*(0.053)	0.343*(0.032)	0.550*(0.046)	0.488 (0.063)	0.550 (0.015)
Taekwondo	f	4	0.685*(0.061)	0.954 (0.088)	0.267*(0.019)	0.508*(0.042)	0.396*(0.021)	0.537*(0.011)
	m	5	0.739*(0.048)	0.934*(0.048)	0.305*(0.020)	0.525*(0.021)	0.423 (0.013)	0.547 (0.022)
Triathlon	f	5	0.670*(0.022)	0.903 (0.045)	0.270*(0.008)	0.458*(0.016)	0.400*(0.017)	0.551*(0.011)
	m	10	0.739 (0.029)	0.915*(0.022)	0.315*(0.012)	0.500*(0.011)	0.411 (0.012)	0.555 (0.012)
Ultimate Frisbee	f	15	0.695*(0.037)	0.988 (0.047)	0.280*(0.017)	0.511*(0.031)	0.405*(0.020)	0.552*(0.010)
	m	9	0.772*(0.027)	0.980*(0.029)	0.321*(0.017)	0.527*(0.014)	0.423 (0.015)	0.562 (0.009)
Volleyball (Beach)	f	9	0.707*(0.057)	0.985 (0.058)	0.286 (0.020)	0.508*(0.034)	0.404*(0.039)	0.567*(0.015)
	m	9	0.783*(0.026)	0.992*(0.033)	0.350*(0.013)	0.549*(0.023)	0.406 (0.017)	0.565 (0.014)
Sum	f	105	0.692 (0.050)	0.966*(0.061)	0.283*(0.024)	0.502*(0.037)	0.413 (0.030)	0.554*(0.015)
	m	167	0.761 (0.075)	0.946*(0.072)	0.323*(0.042)	0.516 (0.051)	0.427 (0.036)	0.558*(0.015)

Asterisks (*) mark normally-distributed data. Abbreviations: waist girth (*w*), gluteal (110) girth (*g*), biceps girth with arm flexed and tensed (*b*), thigh girth at the side front thigh (*t*), waist-to-height ratio (W=*w*/*h*), leg-to-height ratio (L=*l*/*h*). (a)Kenyan long-distance runners, (d)SAT data was published in the Int J Sports Med, 2020 (106), (c)parts published in the Scan J Med Sci Sports, 2019 (58), (b)Archery, trap, skeet.

Anthropometric characteristics in terms of waist girth (*w*), gluteal girth (*g*), biceps girth with the dominated arm flexed and tensed (*b*) according to the ISAK protocol, thigh girth at the side front thigh (*t*) according to the IASMS protocol, and the waist-to-height-ratio (W = *w*/*h*) and leg-to-height-ratio (L = *l*/*h*) indices are shown in Table 17. There was a significant difference between the circumference of *w* (*Z* = -7.836, p <0.001), *g* (*Z* = -2.365, p = 0.018), *b* (*Z* = -7.962, p <0.001), *t* (*Z* = -2.550, p = 0.011), W (*Z* = -3.291, p = 0.001), and L (*Z* = -2.712, p = 0.007) between females and males.

Anthropometry – differences between groups of sports, separated by sex.

A Kruskal-Wallis (*H*) test showed that there were statistically significant differences of *w* (*H*(10, N = 98) = 23.104, p = 0.010), *g* (*H*(10, N = 97) = 38.451, p < 0.001), *b* (*H*(10, N = 103) = 50.039, p < 0.001) , *t* (*H*(10, N = 101) = 33.770, p < 0.001), W (*H*(10, N = 98) = 22.737, p < 0.012), and L (*H*(10, N = 95) = 36.094, p < 0.001) between elite female athletes competing in different sports. Pairwise comparisons with adjusted p-values (and calculated effect sizes according to (109)) for all significant anthropometric data are listed in Table 18.

Table 18: Differences of anthropometric parameters in females.
Pairwise comparisons between significant pairs of groups.

WAIST (*w*) girth in females			
Sample 1- Sample 2 (group of sport)	z-scores	adjusted p-values	r
Athletics-Judo	-3.405	0.036	0.63
Athletics-Hockey	-3.806	0.008	0.63
GLUTEAL (*g*) girth in females			
Athletics-Ultimate Frisbee	-4.098	0.002	0.89
Athletics-Hockey	-4.806	0.000	0.79
Triathlon-Hockey	3.327	0.048	0.56
BICEPS (*b*) girth in females			
Athletics-Hockey	-3.633	0.015	0.60
Athletics-Judo	-6.007	0.000	1.12
Orienteering-Judo	3.790	0.008	0.72
Triathlon-Judo	3.517	0.024	0.68
Ultimate Frisbee-Judo	3.407	0.036	0.56
Hockey-Judo	-3.853	0.006	0.53
THIGH (*t*) girth in females			
Athletics-Judo	-3.563	0.020	0.67
Athletics-Ultimate Frisbee	-3.904	0.005	0.83
Athletics-Hockey	-4.579	0.000	0.76
Athletics-Badminton	-3.602	0.017	1.14
WAIST-TO-HEIGHT-RATIO (W) in females			
Athletics-Hockey	-3.656	0.014	0.60
LEG-TO-HEIGHT-RATIO (L) in females			
Taekwondo-Volleyball	-3.615	0.017	1.04
Taekwondo-Athletics	4.283	0.001	1.35
Hockey-Volleyball	-3.324	0.049	0.55
Hockey-Athletics	4.304	0.001	0.73
Ultimate Frisbee-Athletics	3.361	0.043	0.59

Abbreviations: Calculated effect size for pairwise comparisons: $r = z/\sqrt{N}$; intervals for r: 0.1 to 0.3: small effect; 0.3 to 0.5: intermediate effect; ≥0.5: strong effect (109). Remark: Female athletes competing in the heavyweight category (N=1 in Judo, N=1 in Taekwondo) were not included in the analyses

In the male group, the Kruskal-Wallis test showed also statistically significant differences of w ($H(10, N = 158) = 74.771$, $p < 0.001$), g ($H(10, N = 159) = 82.459$, $p < 0.001$), b ($H(10, N = 163) = 110.733$, $p < 0.001$) , t ($H(10, N = 162) = 79.806$, $p < 0.001$), W ($H(10, N = 158) = 68.476$, $p < 0.001$) , and L ($H(10, N = 160) = 45.621$, $p < 0.001$) between sports. Pairwise comparisons with adjusted p-values (and calculated effect sizes according to (109)) for all significant anthropometric data are listed in Table 19.

Table 19: Differences of anthropometric parameters in males.
Pairwise comparisons between significant pairs of groups.

WAIST (*w*) girth in males			
Sample 1- Sample 2 (group of sport)	z-scores	adjusted p-values	r
Athletics-Badminton	-3.728	0.011	0.61
Athletics-Boxing	-4.346	0.001	0.75
Athletics-Ultimate Frisbee	-4.387	0.001	0.75
Athletics-Judo	-6.852	0.000	0.86
Athletics-Hockey	-6.498	0.000	0.89
Athletics-Volleyball	-3.896	0.005	0.71
Athletics-Shooting	-6.000	0.000	1.06
Orienteering-Shooting	-3.446	0.031	0.81
GLUTEAL (*g*) girth in males			
Athletics-Boxing	-3.368	0.042	0.58
Athletics-Judo	-6.414	0.000	0.80
Athletics-Badminton	-4.949	0.000	0.81
Athletics-Ultimate Frisbee	-5.193	0.000	0.89
Athletics-Hockey	-7.619	0.000	1.05
Athletics-Volleyball	-4.551	0.000	0.83
Athletics-Shooting	-5.287	0.000	0.93
BICEPS (*b*) girth in males			
Athletics-Ultimate Frisbee	-3.584	0.019	0.61
Athletics-Hockey	-5.633	0.000	0.77
Athletics-Boxing	-4.838	0.000	0.83
Athletics-Shooting	-4.541	0.000	0.80
Athletics-Volleyball	-5.937	0.000	1.02
Athletics-Judo	-9.371	0.000	1.17
Orienteering-Volleyball	-3.844	0.007	0.86
Orienteering-Judo	5.333	0.000	0.75
Badminton-Judo	-4.122	0.002	0.58
Triathlon-Judo	3.393	0.038	0.49
Hockey-Judo	-3.435	0.033	0.42
THIGH (*t*) girth in males			
Athletics-Badminton	-4.214	0.001	0.69
Athletics-Ultimate Frisbee	-4.423	0.001	0.76
Athletics-Judo	-6.808	0.000	0.85
Athletics-Hockey	-7.057	0.000	0.97
Athletics-Shooting	-4.537	0.000	0.81
Athletics-Volleyball	-5.919	0.000	1.02
WAIST-TO-HEIGHT-RATIO (W) in males			
Athletics-Hockey	-4.699	0.000	0.65
Athletics-Boxing	-3.416	0.035	0.59
Athletics-Judo	-6.793	0.000	0.86
Athletics-Shooting	-5.085	0.000	0.90
Orienteering-Judo	4.122	0.002	0.59
Orienteering-Shooting	-3.798	0.008	0.90

LEG-TO-HEIGHT-RATIO (L) in males			
Hockey-Athletics	5.787	0.000	0.79
Shooting-Athletics	3.620	0.016	0.64
Triathlon-Athletics	3.573	0.019	0.60
Judo-Athletics	4.822	0.000	0.61

Abbreviations: Calculated effect size for pairwise comparisons: r = z/√N; intervals for r: 0.1 to 0.3: small effect; 0.3 to 0.5: intermediate effect; ≥0.5: strong effect (109).

Table 20: Subcutaneous adipose tissue (SAT) thickness sums, and fasciae of the athlete groups separated by sex and sports.

SPORTS MEAN (±SD)	**sex**	**n**	**age** [years]	$D_{\mathrm{I, MEDIAN}}$	$D_{\mathrm{E, MEDIAN}}$ [mm] (MIN; MAX; IQR)	$D_{\mathrm{F, MEDIAN}}$	$D_{\mathrm{P, MEDIAN}}$ [%] (MIN; MAX; IQR)
Athletics(a,b)	*f*	*7*	*24.1* (5.6)*	*57.6*(20.2; 82.1; 45.4)*	*49.6*(14.0; 75.3; 43.8)*	*6.8* (6.2; 8.2; 1.4)*	*13.9*(8.3; 30.9; 13.8)*
	m	*25*	*27.2* (3.3)*	*8.6 (3.0; 36.2; 10.7)*	*6.7 (2.3; 28.0; 7.0)*	*2.8 (0.4; 8.2; 3.9)*	*29.5*(13.4; 46.9; 8.7)*
Badminton	f	3	21.0* (3.6)	73.8*(40.9; 125.0; n.a.)	66.2*(34.8; 118.4; n.a.)	6.6*(6.1; 7.5; n.a.)	10.2 (5.3; 15.0; n.a.)
	m	12	22.5* (4.3)	21.9 (10.4; 67.0; 39.9)	17.2 (8.1; 60.4; 38.5)	4.7*(2.3; 9.0; 3.0)	17.3*(7.3; 27.9; 8.1)
Boxing	f	2	25.0 (5.7)	69.1 (50.2; 87.9; n.a.)	63.6 (45.4; 81.9; n.a.)	5.4 (4.8; 6.0; n.a.)	8.2 (6.8; 9.6; n.a.)
	m	10	21.0 (3.4)	27.0 (12.8; 102.1; 41.8)	20.8 (9.7; 96.6; 39.4)	6.0*(3.1; 8.1; 2.7)	19.1*(5.4; 27.2; 13.3)
Hockey	f	30	22.5* (3.0)	91.0*(34.3; 145.4; 38.2)	83.0*(29.8; 138.9; 39.6)	6.4*(3.0; 8.2; 1.8)	7.0 (3.4; 13.3; 4.3)
	m	28	23.6* (3.6)	32.4*(9.2; 68.5; 26.8)	26.4*(7.0; 62.3; 25.5)	6.0*(1.9; 8.8; 2.3)	19.3*(9.0; 31.4; 10.3)
Judo(c)	f	23	22.5 (5.0)	66.1*(8.8; 119.0; 20.5)	59.7*(6.5; 110.2; 21.0)	5.8*(2.3; 8.8; 3.1)	8.4 (5.5; 26.2; 2.8)
	m	41	24.1 (5.0)	20.7 (3.0; 117.4;14.9)	16.0 (2.3; 109.9; 14.4)	5.2* (0.7; 8.0; 2.0)	21.9*(5.5; 50.8; 12.3)
Orienteering	f	6	23.2 (2.5)	56.4*(52.2; 65.0; 7.5)	49.3*(47.0; 58.3; 6.3)	6.8*(5.2; 7.5; 1.0)	12.0 (9.9; 13.6; 2.4)
	m	11	21.6 (3.7)	25.4* (5.0; 37.9; 11.3)	18.2*(4.0; 31.2; 8.5)	5.9*(1.0; 7.7; 3.4)	23.1*(17.8; 28.4; 4.6)
Shooting(d)	f	1					
	m	7	33.4* (12.8)	89.7*(38.4; 129.6; 68.4)	80.8*(31.8; 123.0; 67.7)	6.6*(6.0; 9.3; 2.7)	9.9*(5.1; 17.2; 8.7)
Taekwondo	f	4	23.0* (1.8)	65.0*(36.0; 83.7; 42.3)	60.2*(30.8; 75.2; 38.9)	5.9*(3.1; 8.5; 4.4)	9.3 (6.0; 14.4; 6.8)
	m	5	21.4* (2.9)	23.9*(5.6; 30.6; 17.5)	20.1* (4.3; 23.7; 13.8)	4.0*(1.3; 7.3; 3.8)	20.7*(16.0; 23.8; 6.5)
Triathlon	f	5	23.2* (3.6)	43.4*(32.7; 67.3; 21.2)	37.0*(29.2; 61.8; 21.1)	5.5*(3.5; 7.0; 2.8)	10.8 (8.1; 18.9; 8.0)
	m	10	21.9 (4.1)	17.9*(5.4; 32.5; 16.8)	13.4*(4.1; 27.2; 14.6)	4.2*(1.4; 6.2; 2.8)	24.1*(14.8; 29.9; 6.5)
Ultimate Frisbee	f	15	26.5* (3.6)	84.5*(50.3; 121.7; 28.9)	78.5*(43.5; 114.1; 29.2)	6.4*(4.4; 8.0; 2.6)	7.1 (4.4; 13.5; 2.6)
	m	9	27.3* (3.5)	40.6*(24.4; 56.1;14.8)	36.0*(18.5; 48.9; 14.0)	6.1*(4.2; 7.2; 2.0)	14.0*(10.4; 24.0; 4.5)
Volleyball (Beach)	f	9	20.2 (2.1)	76.0*(41.5; 131.9; 34.8)	69.3*(35.9; 123.2; 33.0)	6.8*(4.9; 9.0; 2.8)	10.1 (6.6; 13.6; 5.2)
	m	9	22.1 (2.7)	25.0*(3.7; 36.7; 13.7)	17.7*(3.4; 30.5; 12.5)	6.1 (0.3; 7.4; 2.1)	23.8*(7.3; 33.3; 9.5)
Sum	f	105	23.3 (4.5)	72.5*(8.8; 145.4; 34.5)	65.2*(6.5; 138.9; 35.2)	6.6 (2.3; 9.0; 2.2)	8.7 (3.4; 30.9; 4.6)
	m	167	24.2 (5.3)	24.0 (3.0; 129.6; 24.3)	17.9 (2.3; 123.0; 20.8)	5.3 (0.3; 9.3; 3.0)	21.1 (5.1; 50.8; 10.7)

Asterisks (*) mark normally-distributed data. Abbreviations: subcutaneous adipose tissue (SAT) thickness sums (D_I, and D_E). The index I refers to thickness sums including embedded fibrous structures, the index E refers to thickness sums excluding embedded fibrous structures, Percentages (P) of fibrous structures (F) embedded in the SAT: P= $100F/D_I = 100(D_I - D_E)/D_I$. (a)Kenyan long-distance runners, (b)SAT data was published in the Int J Sports Med, 2020 (106), (c)parts published in the Scan J Med Sci Sports, 2019 (58), (d)Archery, trap, skeet.

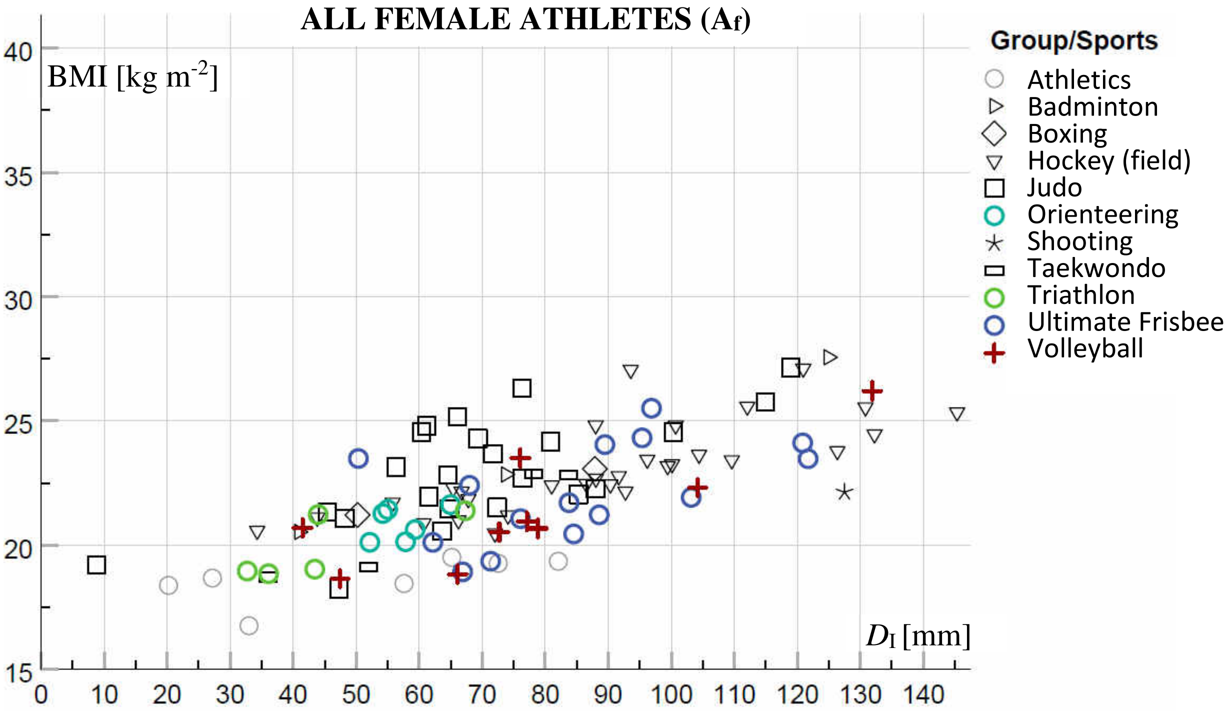


Figure 35: Relationship between subcutaneous adipose tissue (SAT) thickness sums (D_I) including embedded fibrous structures, and BMI for the female athletes (A_f) group (N=105).
Remark: Female athletes competing in the heavyweight category (N=1 Judo; D_I = 119.0 mm, N=1 Taekwondo; D_I = 78.1 mm) were not included in the analyses but shown.

Figure 35 shows the relationship between SAT thickness sums D_I and BMI $\left(BMI = \frac{m}{h^2}\right)$ in elite female athletes (A_f). There was a significant positive correlation between D_I and BMI in A_f (r = 0.713, p <0.01). When using the MI_1 ($MI_1 = 0.53 \cdot m/(hs)$); instead of BMI, the results remain almost the same (r = 0.721, p < 0.01). Female athletes competing in the heavyweight category (N=1 Judo; D_I = 119.0 mm, N=1 Taekwondo; D_I = 78.1 mm) were not included in the analyses but are shown in Figure 35.

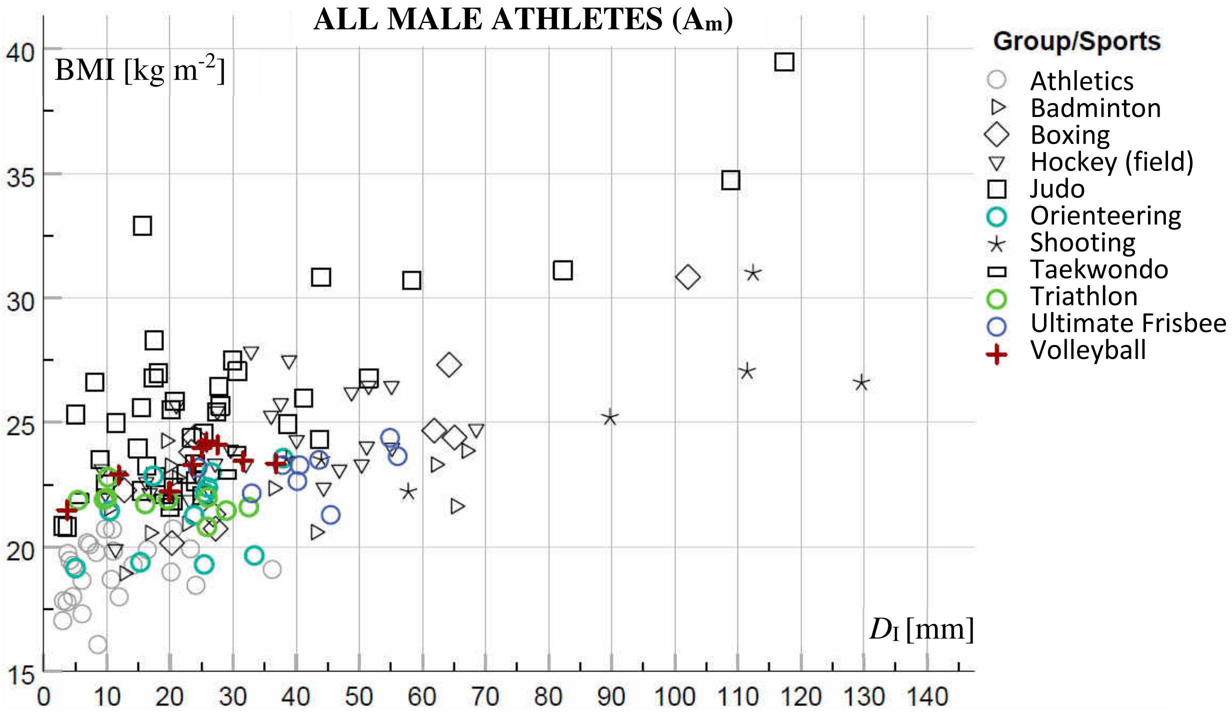


Figure 36: as in Figure 35 but for all adult male (A_m) athletes (N=166).
Remark: Athletes competing in the heavyweight, and super heavyweight category (N=2 Judo; D_I = 108.9, and 117.4 mm, and N=1 Boxing; D_I = 102.1 mm) were shown but not included in the analyses. One judoka was excluded due to one missing body site.

Figure 36 shows possible correlations between D_I and BMI in all male athletes (A_m). There was a significant positive correlation between these variables ($r_s = 0.554$, $p < 0.01$). Using the MI_1 instead of BMI, the results remain almost the same ($r_s = 0.544$, $p < 0.01$). Athletes competing in the heavyweight (N=2 Judo; D_I = 108.9, and 117.4 mm), and super heavyweight category (N=1 Boxing; D_I = 102.1 mm) were not included in the analyses but are shown in Figure 36.

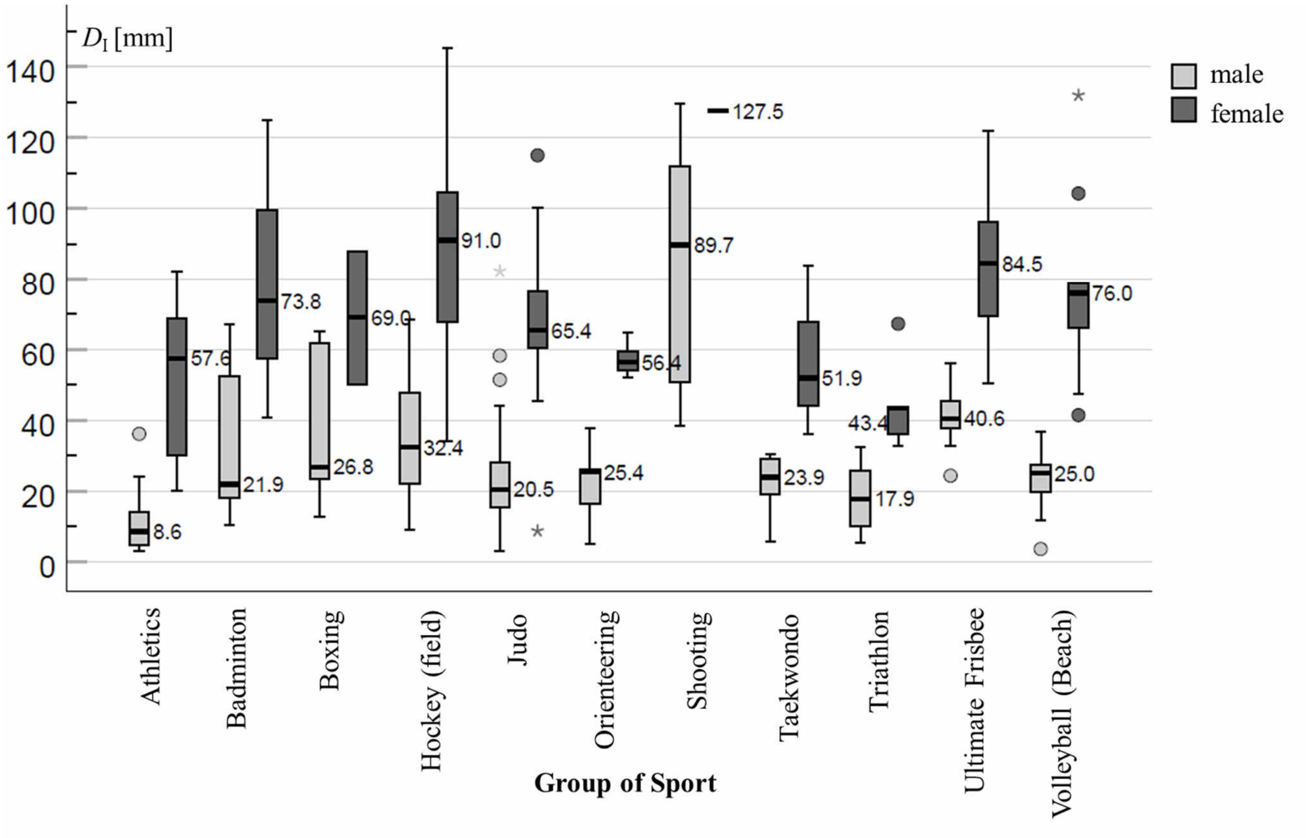


Figure 37: Subcutaneous adipose tissue (SAT) thickness sums including embedded fibrous structures (D_I) of all elite female and male athletes competing in different sports.
Remark: in the male group, heavyweight (two judokas, D_I = 108.9, and 117.4 mm, and super heavyweight category, one Boxer, D_I = 102.1 mm) were excluded. In the female group, heavyweight category (one judoka with D_I = 119.0 mm, and one Taekwondo fighter with D_I = 78.1 mm) were excluded.

Figure 37 shows the SAT thickness sums including (D_I) embedded fibrous structures. A Mann-Whitney-U-Test or t-test (according to distribution) was calculated to determine whether there were differences in D_I between female and male athletes competing in the same sport. Statistically significant differences between elite females and males were calculated in long-distance running (athletics) ($Z = -3.715$, $p < 0.001$), badminton ($Z = -2.021$, $p = 0.048$), hockey (field) ($t(56) = -9.691$, $p < 0.001$), judo ($Z = -5.522$, $p < 0.001$), and orienteering ($t(14.88) = -10.064$, $p < 0.001$). No calculations were performed for shooting (archery, trap, and skeet) due to the small number of females (N=1). In triathlon, there was a statistically significant difference between females and males (t(6.06) = -3.892, $p = 0.008$) as well as in ultimate frisbee (t(21.40) = -6.977, $p < 0.001$), and volleyball (beach) (t(10.09) = -5.589, $p < 0.001$). There was no statistically significant difference between females and males in taekwondo (t(2.42) = -2.418, $p < 0.115$), and boxing ($Z = -1.414$, $p = 0.218$), although this should be interpreted with caution due to the small numbers of female participants (see Table 20).

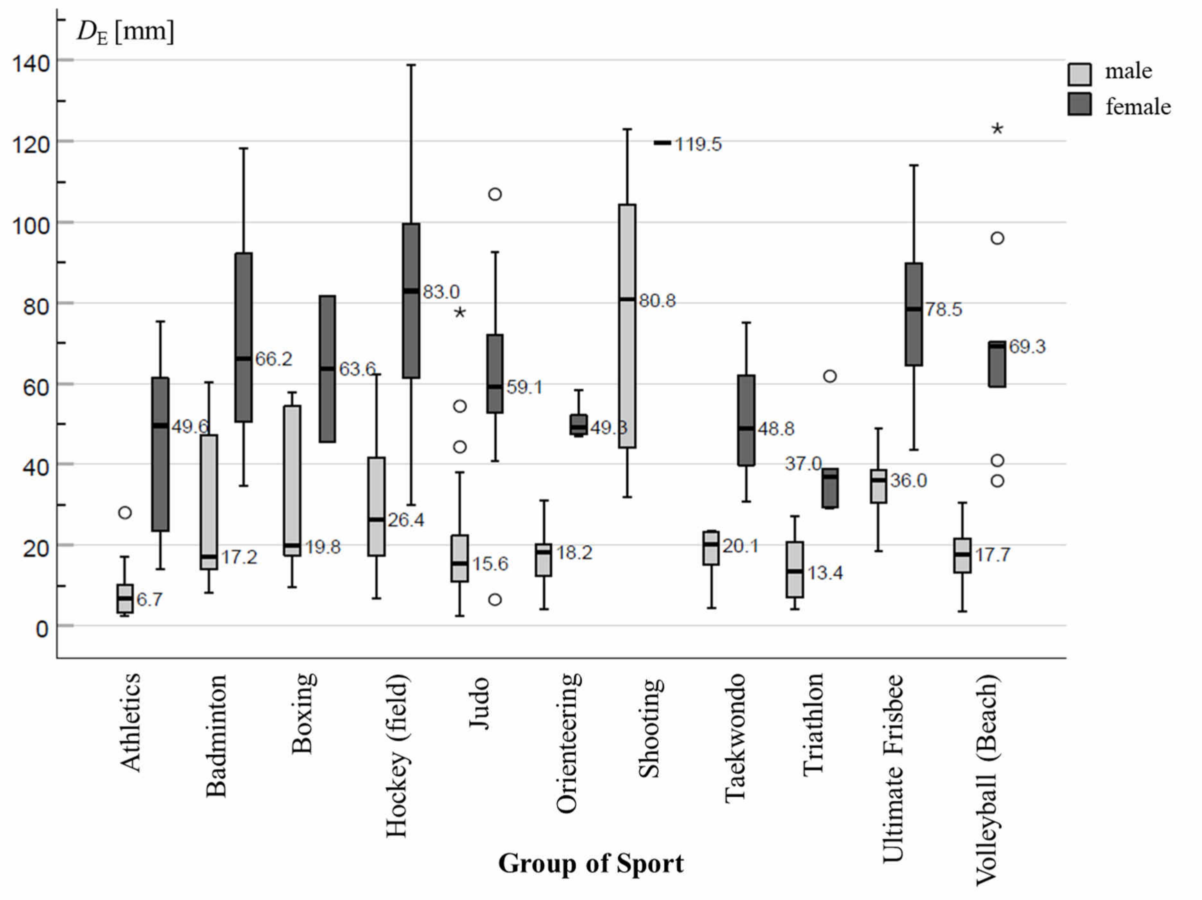


Figure 38: as in Figure 37 but excluding (index E) embedded fibrous structures in the SAT thickness sums (D_E).

Remark: in the male group, the heavyweight (two judokas, $D_I = 108.9$, and 117.4 mm) and super heavyweight categories (one Boxer, $D_I = 102.1$ mm) were excluded. In the female group, the heavyweight category (one judoka with $D_I = 119.0$ mm, and one Taekwondo fighter with $D_I = 78.1$ mm) was excluded.

Figure 38 shows the SAT thickness sums (D_E) excluding (index E) embedded fibrous structures. A Mann-Whitney-U-Test or t-test (according to distribution) was calculated to determine whether there were differences in D_E between female and male athletes competing in the same sport. Statistically significant differences between elite females and males were calculated in long-distance running (athletics) ($Z = -3.715$, $p < 0.001$), badminton ($Z = -2.021$, $p = 0.048$), hockey (field) (t(56) = -9.826, $p < 0.001$), judo ($Z = -5.522$, $p < 0.001$), and orienteering (t(14.96) = -11.353, $p < 0.001$). In shooting (archery, trap, skeet), no possible differences between sexes were calculated due to the small number of females (N=1). Further, in triathlon, there was a statistically significant difference between females and males (t(5.55) = -3.787, $p = 0.011$) as well as in ultimate frisbee (t(22) = -5.954, $p < 0.001$), and volleyball (beach) (t(9.54) = -5.693, $p < 0.001$). There was no statistically significant difference between females and males in taekwondo (t(2.32) = -2.568,

$p < 0.107$), and boxing ($Z = -1.414$, $p = 0.218$), although this should be interpreted with caution due to the small numbers of females (see Table 20).

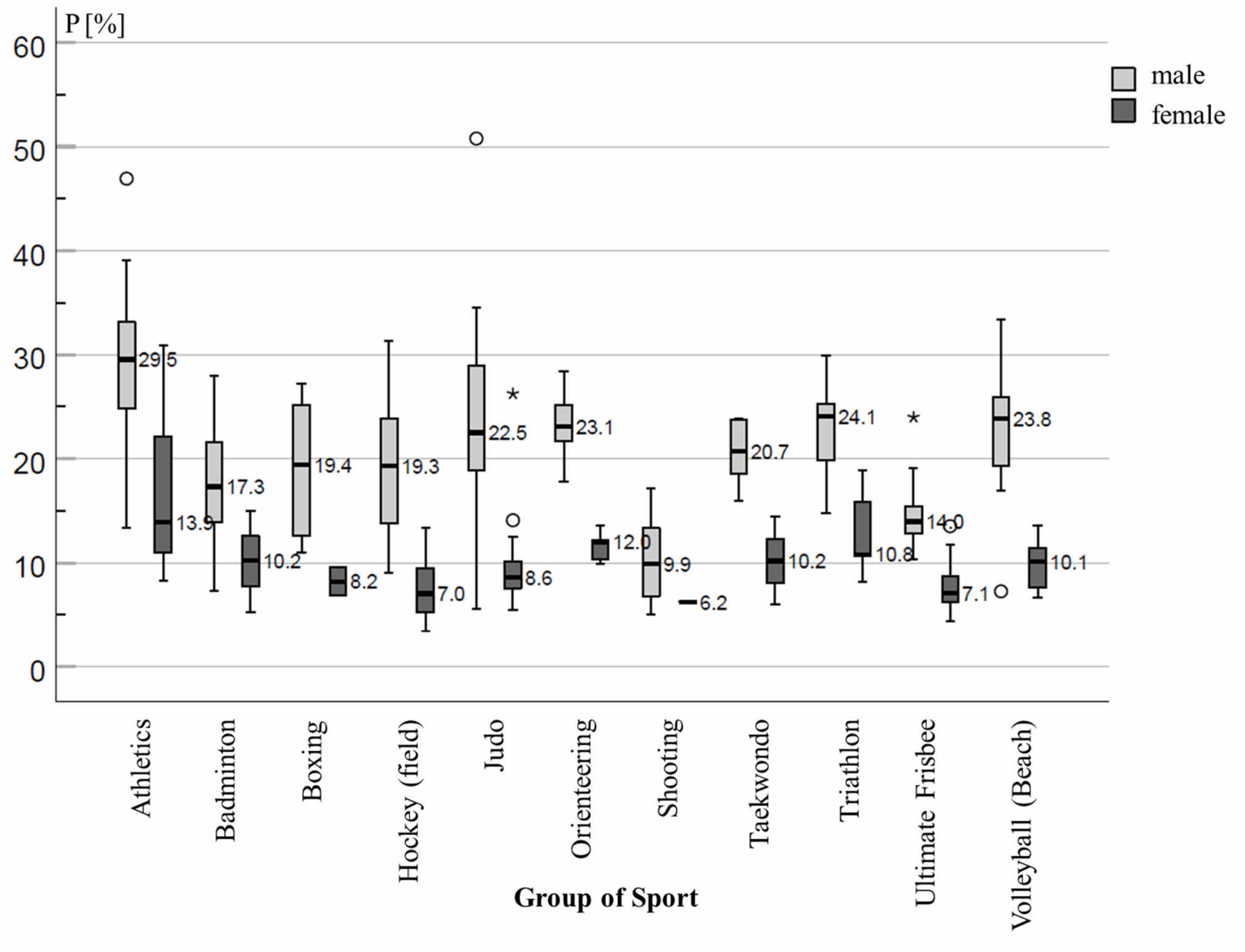


Figure 39: Percentages (P) of fibrous structures (F) embedded in the subcutaneous adipose tissue (SAT).

Abbreviations: $P = 100F/D_I = 100(D_I-D_E)/D_I$. SAT thickness sums D_I including (index I) or excluding (index E) embedded fibrous structures. Remark: in the male group, the heavyweight (two judokas, $D_I = 108.9$, and 117.4 mm) and super heavyweight categories (one Boxer, $D_I = 102.1$ mm) were excluded. In the female group, the heavyweight category (one judoka with $D_I = 119.0$ mm, and one Taekwondo fighter with $D_I = 78.1$ mm) was excluded.

Figure 39 shows percentages (P) of fibrous structures (F) embedded in the SAT. A Mann-Whitney-U-Test or t-test (according to distribution) was calculated to determine whether there were differences in P between female and male athletes competing in the same sport. Statistically significant differences between elite females and males were calculated in long-distance running (athletics) ($t(30) = -3.846$, $p = 0.001$), boxing ($Z = -2.121$, $p = 0.034$), hockey (field) ($Z = -6.209$, $p < 0.001$), judo ($Z = -5.354$, $p < 0.001$), and orienteering ($Z = -3.317$, $p = 0.001$). In shooting (archery, trap, skeet), no possible differences between sexes were calculated due to the small number of females (N=1). In taekwondo, there was a statistically significant difference between females and males (Z = -2.236, $p = 0.025$) as well as in triathlon ($Z = -2.694$, $p = 0.007$), ultimate frisbee ($Z = -3.667$, $p < 0.001$), and volleyball (beach) ($Z = -2.958$, $p = 0.003$). There was no statistically significant difference between females and males in badminton ($Z = -1732$, $p = 0.083$), although this should be interpreted with caution due to the small numbers of females (N=3, see Table 20).

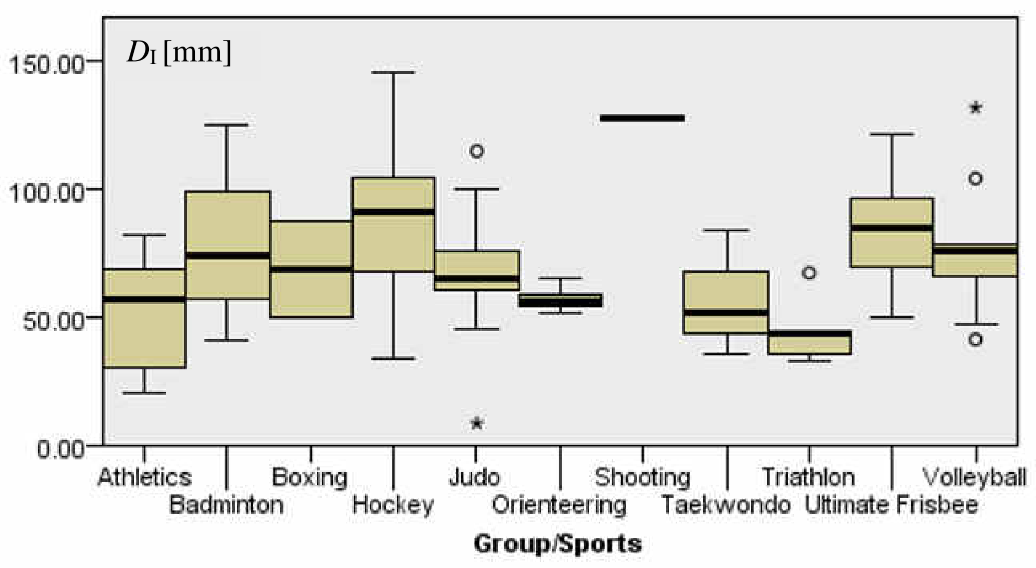


Figure 40: Boxplots – independent samples in female athletes.

A Kruskal-Wallis (H) test showed that there was a statistically significant difference in D_I between elite female athletes competing in different sports $H(10, N = 103) = 34.153$, $p < 0.001$). Pairwise comparisons with adjusted p-values showed that there was only a significant difference in D_I between female athletes competing in triathlon and female hockey players ($z = 3.617$, $p = 0.016$, $r = 0.61$). In this group of international-competing female athletes, triathletes had the lowest SAT thickness sums in terms of D_I ($D_{I,MEDIAN}$ = 43.4), followed by females competing in taekwondo ($D_{I,MEDIAN} = 51.9$) (Figure 37).

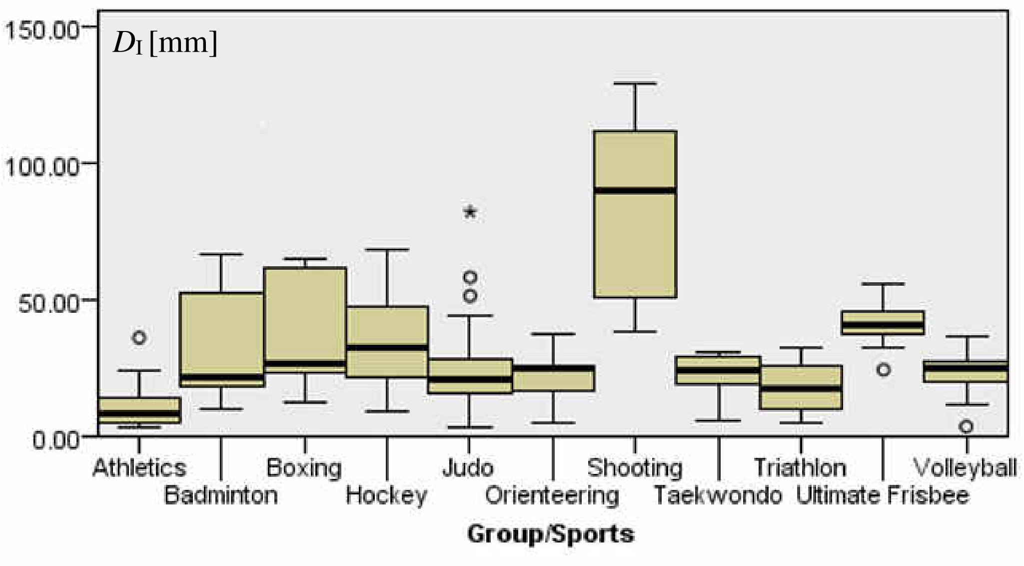


Figure 41: Boxplots – independent samples in male athletes.

A Kruskal-Wallis (*H*) test showed that there was a statistically significant difference of D_I between elite male athletes competing in different sports $H(10, N = 163) = 62.078$, $p < 0.001$). Pairwise comparisons with adjusted p-values (and calculated effect sizes according to (109)) showed that there were significant differences in D_I between long-distance runners (athletics) and judokas (z = -3.463, p = 0.029, r = 0.44), badminton players (z = -3.622, p = 0.016, r = 0.60), boxers (z = -3.824, p = 0.007, r = 0.66), hockey (field) players (z = -5423, p <0.001, r = 0.74), ultimate frisbee players (z = -5.210, p <0.001, r = 0.89), and shooters (z = -5.863, p <0.001, r = 1.0). Statistically significant differences were also calculated between male triathletes and shooters (z = 3.864, p = 0.006, r = 0.94), and between judokas and shooters (z = -3.927, p = 0.005, r = 0.59). The median D_I values for all athletes separated by sex and sports (including heavy weight categories) can be found in Table 20, or excluding heavy weight categories in combat sports in Figure 37. In this group of international-competing athletes, Kenyan long-distance runners had the lowest SAT thickness sums in terms of D_I ($D_{I,MEDIAN} = 8.6$), followed by triathletes ($D_{I,MEDIAN} = 17.9$).

Table 21: Differences in SAT in terms of D_I: Pairwise comparisons between significant pairs of groups.

Males			
Sample 1- Sample 2 (group of sport)	z-scores	adjusted p-values	r
Athletics-Judo	-3.463	0.029	0.44
Athletics-Badminton	-3.622	0.016	0.60
Athletics-Boxing	-3.824	0.007	0.66
Athletics-Hockey	-5.423	0.000	0.74
Athletics-Ultimate Frisbee	-5.210	0.000	0.89
Athletics-Shooting	-5.863	0.000	1.04
Triathlon-Shooting	3.864	0.006	0.94
Judo-Shooting	-3.927	0.005	0.59
females			
Triathlon-Hockey	3.617	0.016	0.61

Abbreviations: Calculated effect size for pairwise comparisons: $r = z/\sqrt{N}$; intervals for r: 0.1 to 0.3: small effect; 0.3 to 0.5: intermediate effect; ≥0.5: strong effect (109), (SAT) subcutaneous adipose tissue, (D_I) sum of eight body sites included embedded fibrous structures in the SAT.

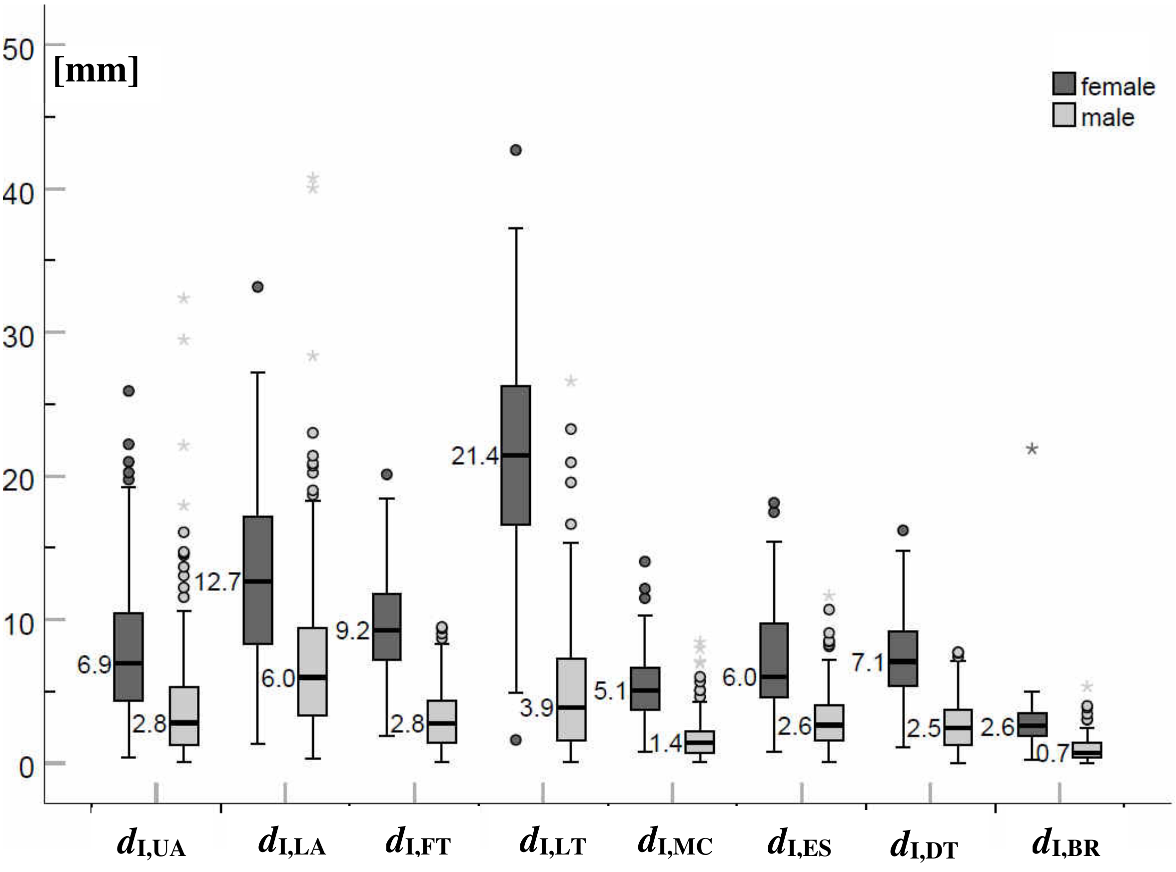


Figure 42: Subcutaneous adipose tissue thickness (SAT) patterning (d_I) at eight standardised sites in elite female and male athletes.

Abbreviations: (UA) upper abdomen, (LA) lower abdomen, (FT) front thigh, (LT) lateral thigh, (MC) medial calf, (ES) erector spinae, (DT) distal triceps, (BR) brachioradialis. Index I refers to including embedded fibrous structures. Remark: in the male group, the heavyweight (two judokas, $D_I = 108.9$, and 117.4 mm, in Figure 36), and super heavyweight categories (one boxer, D_I = 102.1 mm) were excluded. In the female group, the heavyweight category (one judoka with D_I = 119.0 mm, and one Taekwondo fighter with D_I = 78.1 mm, in Figure 35) was excluded.

The boxplots in Figure 42 show differences at defined body sites (d_I, including embedded fibrous structures) between female and male elite athletes. At all eight body sites, there were significant differences between females and males (UA (Z = -7.406, p<0.01), LA (Z = -7.773, p<0.01), FT (Z = -12.590, p<0.01), LT (Z = -12.735, p<0.01), MC (Z = -11.472, p<0.01), ES (Z = -9.555, p<0.01), DT (Z = -11.660, p<0.01), and BR (Z = -10.916, p<0.01)). The highest ratio of the median SAT thicknesses including fibrous structures (d_I) was calculated at the lateral thigh site (LT: 21.4/3.9 = 5.5), while the lowest ratio was measured at the site lower abdomen (LA: 12.7/6.0 = 2.1). The ratios of all remaining sites were UA: 6.9/2.8 = 2.5, FT: 9.2/2.8 = 3.3, MC: 5.1/1.4 = 3.6, ES: 6.0/2.6 = 2.3, DT: 7.1/2.5 = 2.8, and BR: 2.6/0.7 = 3.7.

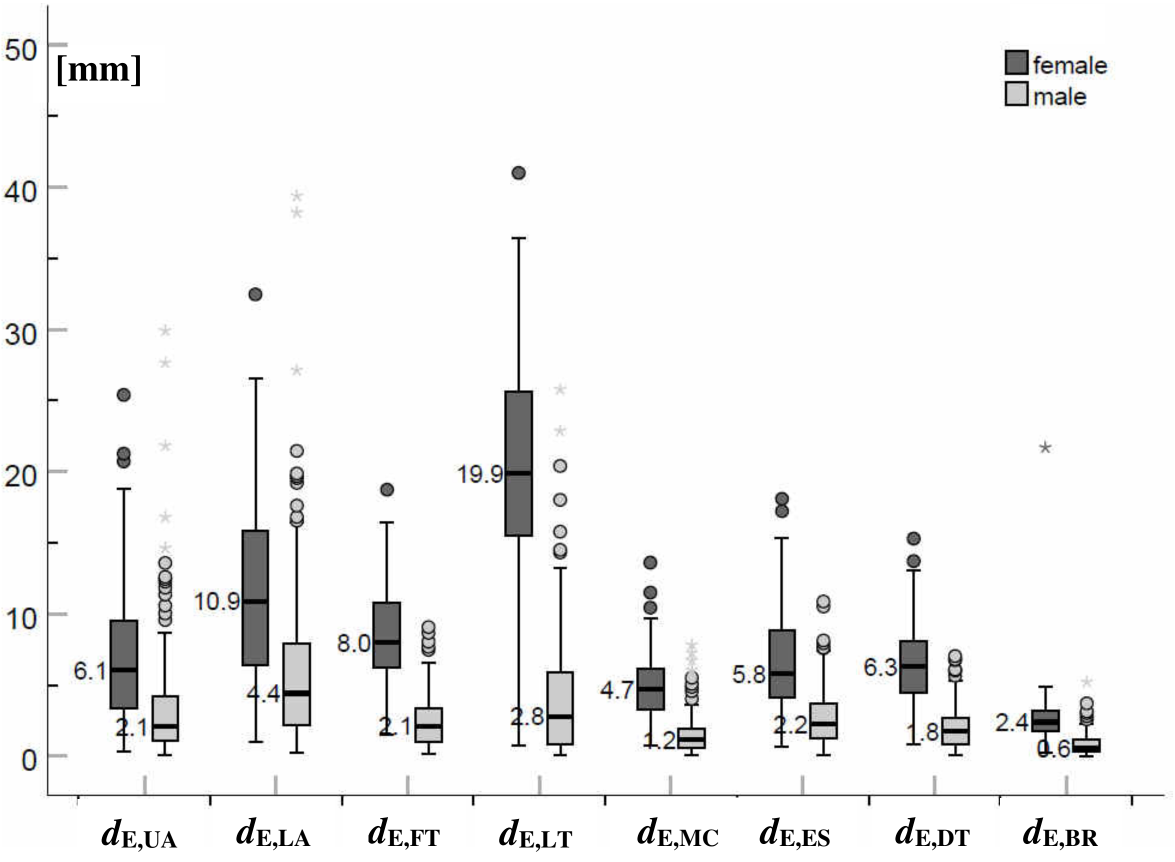


Figure 43: Subcutaneous adipose tissue thickness (SAT) patterning (d_E) in elite female and male athletes.
Abbreviations: (UA) upper abdomen, (LA) lower abdomen, (FT) front thigh, (LT) lateral thigh, (MC) medial calf, (ES) erector spinae, (DT) distal triceps, (BR) brachioradialis. Index E refers to excluding embedded fibrous structures. Remark: in the male group, the heavyweight category (two judokas, D_I = 108.9, and 117.4 mm, in Figure 36), and super heavyweight categories (one boxer, D_I = 102.1 mm)

were excluded. In the female group, the heavyweight category (one judoka with D_I = 119.0 mm, and one Taekwondo fighter with D_I = 78.1 mm, in Figure 35) was excluded.

Figure 43 shows SAT thicknesses at defined body sites excluding fibrous structures in the SAT measurements (d_E). At all eight standardised sites, there were significant differences between international-competing females and males (UA (Z = -7.546, p<0.01), LA (Z = -8.035, p<0.01), FT (Z = -12.580, p<0.01), LT (Z = -12.696, p<0.01), MC (Z = -11.557, p<0.01), ES (Z = -9.697, p<0.01), DT (Z = -11.875, p<0.01), and BR (Z = -11.019, p<0.01)). When fibrous structures embedded in the SAT were excluded (Figure 43) in the measurements, the ratios between females and males were: UA: 6.1/2.1=2.9, LA: 10.9/4.4=2.5, FT: 8.0/2.1=3.8, LT: 19.9/2.8=7.1, MC: 4.7/1.2=3.9, ES: 5.8/2.2=2.6, DT: 6.3/1.8=3.5, and BR: 2.4/0.6=4.0.

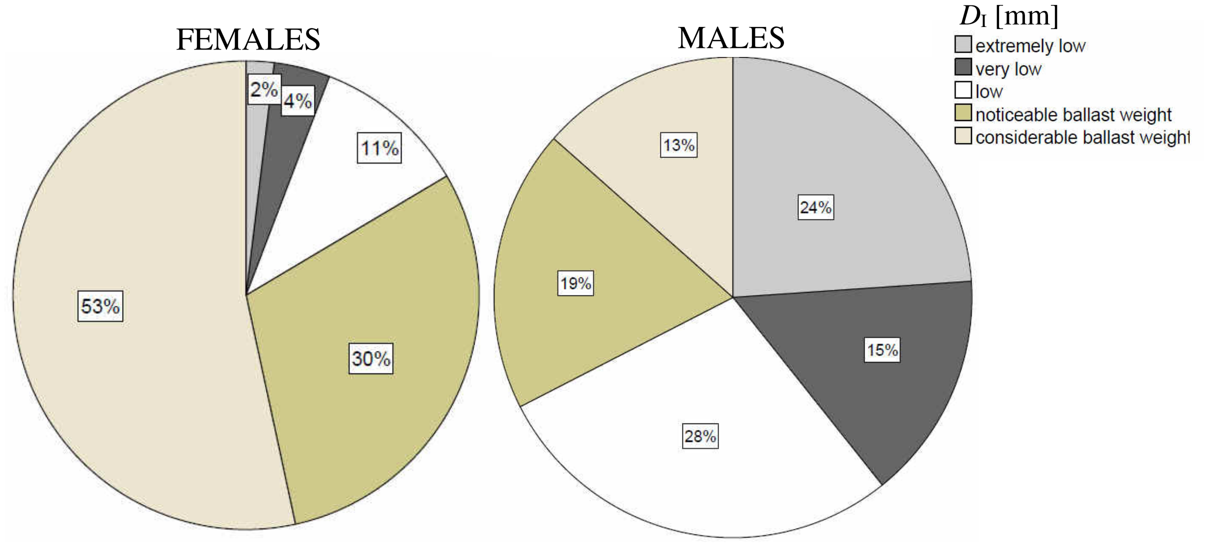


Figure 44: Subcutaneous adipose tissue (SAT) valuation of elite female and male athletes according to preliminary published normative data by Ackland et al. (86).
Abbreviations: SAT sums of eight sites (D_I) in females, and (males): < 25 mm (<12 mm) 'extremely low', 25-35 mm (12-20 mm) 'very low', 35-50 mm (20-30 mm) 'low', 50-70 mm (30-50 mm) 'noticeable ballast weight', >70 mm (>50 mm) 'considerable ballast weight'. Remark: one athlete (0.6 % in the pie chart) was automatically excluded due to one missing body site, analyses were performed excluding heavy weight categories (N=5).

Figure 44 shows a pie chart including SAT valuations in female and male athletes. In the female group (N=103), two athletes had 'extremely low' D_I values, four had 'very low' D_I values, eleven females had 'low' D_I values, 31 females had 'noticeable ballast weight', and 55 had 'considerable ballast weight'. In males, 39 athletes out of 164 (one athlete, 0.6 % in the pie chart, was excluded because of one missing body site) had 'extremely low' D_I values, 25 male athletes had ‘very low’, 46 athletes had ‘low’ D_I values, 31 athletes had ‘noticeable ballast weight’, and 22 male athletes had ‘considerable ballast weight’.

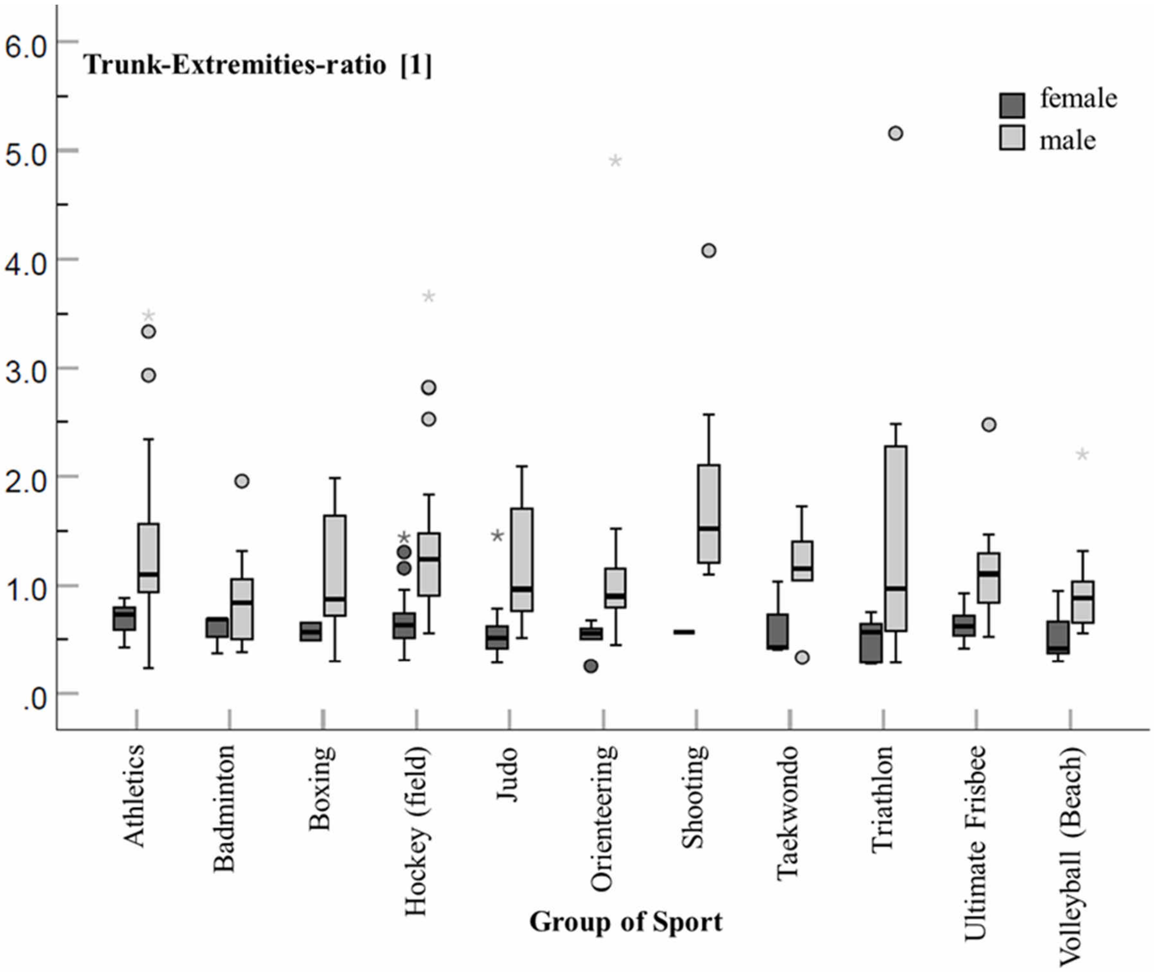


Figure 45: Trunk-to-extremities ratio in female and male elite athletes.
Abbreviations: Trunk-to-extremities ratios [1] were calculated according to the NISOS®-BCA Fat Analysis software, v.4.0. The trunk sites were upper abdomen (UA), lower abdomen (LA), and erector spinae (ES); extremities sites were front thigh (FT), lateral thigh (LT), medial calf (MC), distal triceps (DT), and brachioradialis (BR).

The boxplots in Figure 45 show the trunk-to-extremities ratios of female and male athletes separated by sports. Analyses of females (N=103) and males (N=163) show significant differences in trunk-to-extremities ratios between sexes (Z = -9.587, p<0.01). The median trunk-to-extremities ratio in females was 0.59 (IQR = 0.27), and in males 1.02 (IQR = 0.67), indicating that males carry higher SAT amounts on the trunk. Pairwise comparisons (Kruskal-Wallis test) with adjusted p-values showed that there were no significant differences between trunk-to-extremities ratios in females (*H*(10, N = 103) = 9.633, p = 0.473) competing in different sports, as well as no significant differences in trunk-to-extremities ratios in males (*H*(10, N = 163) = 14.286, p = 0.160) when separated by sports.

4 Discussion

4.1 Competitive Sports and Body Composition

All sports, specific disciplines or playing positions within the same sport have different demands and therefore often require unique body types to compete at the highest level. The impact of body weight, body fat, and muscle mass differs between sports (63), and therefore the priority to optimise body composition may also differ. According to Sundgot-Borgen et al. (1), *"some athletes are genetically suited to the specific anthropometric demands of the sport/weight class in which they compete, but many elite athletes struggle with extreme dieting and eating disorders (EDs) as they attempt to conform to competition regulations that are ill suited to their physique"*. Especially in weight class sports like judo, extreme methods for body weight reduction are common and discussed in the literature (1, 114-116). The acute weight loss strategies – often called 'making weight' – used by judokas involve a range of applied methods with the intentional manipulation of gut content, total body water, and glycogen stores, e.g. training in heated rooms (117), or 'water loading', as a recently-published and well-known method in competitive athletes in combat sports (118). In their review, Franchini et al. (119) summarised that about 90 % of judokas (excluding heavy weight category) reduced their body mass rapidly prior to a competition. The average magnitude of weight loss was about 5 % of body mass, typically during the last five days before the official weigh-in (117).

4.1.1 Elite Judokas.

Here, the mean (N=50; see Figure 20, and Figure 21) body mass reduction before competition was 4.3 % ± 2.0 % (i.e., 3.0 kg ± 1.4 kg), and nineteen athletes had to lose more than 5 % to compete at the chosen weight category, the highest value was 9.2 % (in one male athlete) (58). Similar rapid weight loss practices in other weight class sports were reported by Franchini et al. in 2012 (119). *"In a specific study in competitive judokas, Artioli et al.* (117) *found that "most athletes cut their weight up to five times a year to compete, but a significant percentage reduced their weight up to 10 times a year or more." The most influential persons in leading athletes to reduce their weight were the coaches, but not physicians or dietitians who could provide the best advice for weight management. Reale et al.* (114) *reviewed "acceptable" dietary strategies for Olympic combat sports and discussed how better health and performance outcome may be achieved. However, rapid body mass reduction can be seen as a prohibited method according to the World Anti-Doping Agency*

(WADA) criteria; Artioli et al. (115, 120) *discuss solid arguments why it is "time to ban rapid weight loss from combat sports". Strong data and health considerations indicate that weigh-in procedures should urgently be modified to counteract these unhealthy tendencies in judo, and also in other weight category sports. This could be obtained by modifying the weigh-in regulations and is up to the international combat sport federations. Their medical commissions should take responsibility for the health of their athletes. This was successful in other weight-sensitive sports, for example in ski jumping, where competition rules have been changed by the International Ski Federation (121) to improve the health situation (57, 122, 123)"* (58). In an ACSM Expert Consensus Statement on weight loss in weight category sports, the authors published recommendations for safer 'weight making' practices in weight class sports, including the following: *"If formal weight-category selection programs have not been implemented, clinicians are encouraged to evaluate the athlete's body composition, not BM alone, guide weight class selection, and provide the caveat that minimal weight may not be the optimal performance weight"*(116).

The chosen Olympic combat sports in this study may be classified into striking (boxing and taekwondo) and grappling (judo) (42). Although different physical and physiological characteristics between Olympic combat sports like judo, taekwondo or boxing are recognised (63, 124), there were no significant differences found in this thesis between these groups of athletes regarding D_I values. In female judokas of the WC 48 kg or less measured immediately before the official weigh-in, huge differences in D_I were found. The lowest D_I was 30.7 mm (MI_1 = 19.1 kg m^{-2}), and the highest D_I was 63.6 mm (MI_1 = 20.6 kg m^{-2}), which was approximately twice as high. One female athlete competing in the "middleweight" category (up to 70 kg or less) with D_I = 56.6 mm (MI_1 = 24.6 kg m^{-2}) had lower SAT values than the athlete of in the 'extra-lightweight' category mentioned above. However, practitioners are cautioned to understand that possible correlations at the group level are not usable for individual cases. When excluding the three athletes in the group up to 78 kg or less, there was no significant correlation between WC and D_I (r_s = 0.107; p = 0.769). According to a preliminary assessment schedule (86), the female judoka mentioned above ('extra-lightweight') with D_I = 30.7 mm was in the 'very low' category, and the female judoka with 63.6 mm was in the 'noticeable ballast weight' category.

When measuring elite male judokas (see Figure 17) immediately before the official 'weigh-in', there were also huge differences between D_I values in their chosen weight categories, and no significant correlation between D_I and WC (r_s = 0.347, p = 0.172) was found. For example, in the ‘extra-lightweight’ category of up to 60 kg or less (cn 1 to 4 in Figure 17), the lowest D_{I} was 3.0 mm (MI_{I} = 21.2 kg m^{-2}), whereas the highest D_{I} was 20.6 mm, which was approximately seven times higher. The sum D_{I} of 3.0 mm obtained from the eight measurement sites corresponds to a mean of less than 0.4 mm SAT thickness. Such low SAT thicknesses are not detectable with any other method (2).

According to Ackland and Müller (86), the SAT sums in terms of D_{I} for competitive male athletes lower than 12 mm are categoriesed as ‘extremely low’, and for 20 to 30 mm as ‘low’. The male athlete in the ‘half-heavyweight’ category (up to 100 kg or less) had also a ‘low’ D_{I} value (17.5 mm); his MI_{I} was 28.2 kg m^{-2}. *“The fat values can be used as an important indicator for finding the appropriate weight division for an athlete: athletes who are further away from the extremely low-fat edges have some potential to reduce their weight in the long run without losing muscle and organ mass, instead of applying unhealthy rapid weight reduction practices before a competition”*(58).

The standardised US measurement method enables a reproducibility of about 1 mm for the sum of the SAT thicknesses (D_{I}) of the eight measurement sites; this enables monitoring the body fat (in terms of SAT) with an accuracy of 0.2 kg (22), which is a magnitude lower than the daily body weight fluctuations (22).

When measuring FM and FFM using DXA, small changes in BC may not be accurately detected. In a study by Santos et al. (38), the accuracy of DXA in estimating BC changes in 27 elite male judokas using a 4-C model as the reference method showed that DXA tended to overestimate %FM and FM reductions and underestimate FM gains. In individuals, the LOA were -2.6 to 3.7 kg FM: this is too high to detect BC changes of relevance in elite sports.

In A sub-group of eight elite female judokas (Figure 19) was measured twise: during an international training camp (TC, 2016), and on the day of the official ‘weigh-in’ for an international competition (European Open (EO), 2019). Both D values, D_{I} and D_{E} differed significantly. All female athletes (exept cn 7 in Figure 19; changed to a higher WC) had reduced their body fat**.**

In the period between the two measurement series, two females changed their weight category (WC). Cn 2 changed from the ‘half-lightweight’ (up to 52 kg or less) to ‘extra-lightweight’ (up to 48 kg or less) and had to reduce the body mass by 6 kg. D_{I} changed from: $D_{\mathrm{I,TC}}$ = 72.9 mm to 40.1 mm corresponding to a loss of fat mass of 2.6 kg (mass estimation:

NISOS-BCA Fat Analysis Tool, v.4.0). Another female athlete (cn 7 in Figure 19) changed from the WC 'middleweight' (up to 70 kg or less) to 'half-heavyweight' (up to 78 kg or less) and increased the body mass by 3.2 kg. D_I changed from: $D_{I,TC}$ = 69.3 mm to 82.8 mm corresponding to a gain of fat mass of 1.5 kg.

The remaining six females who did not change their weight category between 2016 and 2019 also reduced their body weight and body fat: the mean loss of body mass was 3.5 kg ± 1.1 kg (i.e., 5.7 % of body mass m), and the mean reduction in D_I was 16.2 mm ± 9.6 mm. The highest value was 5.2 kg (7.7 %). The six athletes from this sub-group reduced their SAT sums over time, which may lead to performance advantages. Among these six athletes, one female had 'low' SAT sums, three had 'noticeable ballast weight', and two females had 'considerable ballast weight' at the first examination (TC). At the second BC assessment (EO), one female had changed to 'very low' SAT sum, two had 'low' SAT sums, and three athletes had 'noticeable ballast weight', while no athlete had 'considerable ballast weight'. Every weight class change is a complex task due to different opponents with their different fighting styles, which need complex adaptive processes (119). It should be considered that performance improvements are not necessarily bound to optaining a WC as low as possible; Franchini et al. (119) mentioned that some world class athletes also competed at the highest level with international success after changing to a heavier weight category, e.g. Ilias Iliadis who won an Olympic medal in the WC up to 81 kg or less in Athens in 2004, and in the WC up to 90 kg or less in London in 2012.

Comparisons between Skinfold and US method in Elite Judokas.

In this thesis comparisons between SFs and US were performed in the group 'elite judokas'.

"When compared to thickness measurements using high resolution US imaging (8, 9), severe errors of skinfold measurements come to light because compressibility of fat and thickness of the skin varies substantially from site to site and among individuals (7). Large deviations were also found in the group of elite judokas investigated here (Figure11 and Figure 12). *For example, two competing athletes who had almost the same SF sums at eight sites (44.9 mm and 45.4 mm) differed by a factor of four when their SAT thicknesses were measured with the standardised US method (the sums of eight sites D_I were 20.0mm and 5.1mm, respectively)"*(58).

In practice, limb circumferences are often used in combination with skinfolds (SFs) to estimate skeletal muscle mass as a fast, and inexpensive alternative to computed axial tomography (CT) or magnetic resonance imaging (MRI) measurement techniques (125). SFs is one of the most commonly-used (until 2013) methods applied in athletes (4). *"When comparing SF and US measurements at the same sites (FT and MC), large deviations were found and the median deviations were significantly higher at FT compared to MC. This can be explained because SFs measure two layers of skin and two layers of fat in an undefined compressed state, and both compressibility and skin thickness differ from site to site and from person to person.* In their study, Silva, Fields, Quitèrio, and Sardinha (126) assessed the usefulness of three anthropometric-based models in tracking BC changes of elite male judokas immediately before a competition. The authors compared changes in %FM, FM, and FFM between a 4-C model (as the criterion method) with SFs (7- or 3-site SF model) and found that SFs are not valid to detect BC changes in these athletes. Considering the poor validity (accuracy) of SFs, the feedback of the data to athletes and coaches may also be inaccurate. There is no consistency in literature: Kasper, Langan-Evans, Hudson, Brownlee, Harper, Naughon, Morton, and Close stated in their recently-published review: *"If the goal is to simply track changes in body fatness over time, it could be argued that skinfold measures may still provide the best solution when reported as a sum of mm rather than a relative percentage value"*(127). This group of authors also presented a set of normative data for the sum of eight SFs in a variety of sports. The two judokas mentioned above with almost the same SFs sum (44.9 mm vs 45.4 mm) would fall in the middle range according to the suggested classification. When using SAT thickness sums in terms of D_I (20.0 mm vs 5.1 mm), the 'extremely low' SAT value (< 12 mm in case two) would not attract attention. *"Listing the athletes according to their SF sums does not result in the same order when listing them according to their US sums of SAT thicknesses. SAT thickness sums (from eight sites) ranged from 5.1 mm to 119.0 mm, and SF sums (from eight sites) from 44.6 mm to 175.8 mm.* The standardised US method measure SAT with an accuracy (8), and reliability (9, 10, 22) not previously achieved by other BC approaches. This approach avoids tissue compression (7), skin and fat deformation, and measures SAT excluding the double layer of skin.

4.1.2 Elite Kenyan Long-Distance Runners.

In a sub-group of nine Kenyan long-distance runners *"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 15 *(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 (128), and in Wajchenberg BL 2000 (18); a chapter on lipid metabolism in athletes can be found in Brooks GA et al. 2005 (129). 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 (130). According to Wilber et al. (131), 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 (132, 133). 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"* (106).

MI_l used for classification of underweight instead of BMI

As mentioned above the BMI is not a useful measure for body fat of athletes (Figure 35 and Figure 36). *"When using the BMI for assessing 'relative body mass', there is a further important limitation: the BMI ignores individual body properties (55). Therefore, W. Müller has developed an improved measure for relative body weight, which considers the sitting height s (and thus, implicitly, also the leg length l): the mass index MI (56, 57, 134). The MI is a modified BMI"*(22). The explanation of the formula ($MI_1 = 0.53 \cdot m/(hs)$) may be found elsewhere (22). *"For a person with long legs, the MI is higher than the BMI, and vice versa for a person with short legs. With the same stature h, a person with shorter legs (large sitting height) can be expected to have higher body mass m because his volume is higher due to the relatively large dimensions of his upper body. Particularly in low weight sports, assessing 'relative body mass' of athletes is a crucial health parameter"(22).*

In the female group including all females (except heavyweight categories), there was a significant positive correlation between D_I and BMI ($r = 0.713$, $p < 0.01$) or MI_l ($r = 0.721$, $p < 0.01$). When applying the WHO criterion for 'underweight' (BMI <18.5 kg m^{-2}) to the adult female athletes studied here, three athletes were to be classified as 'underweight', and one long-distance runner) was even below 17.5 kg m^{-2} (which is one of the criteria for diagnosing anorexia nervosa (135)). When using MI_l instead of BMI, only two females were 'underweight', and one female was below 17.5 kg m^{-2} (BMI = 16.8, MI_1 = 17.3 kg m^{-2}, respectively).

In the male group, including all males (except heavyweight and super heavyweight category) there was also a significant positive correlation between D_I and BMI ($r_s = 0.554$, $p < 0.01$). When using MI_1 instead of BMI, the results are almost the same ($r_s = 0.544$, $p < 0.01$) (Figure 36). When applying the WHO criterion for 'underweight' (BMI <18.5 kg m^{-2}) in the males studied here, seven athletes are to be classified as 'underweight', and three male athletes (all three athletes compete in long-distance running) were even below 17.5 kg m^{-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"(136). 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 (54) 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 (135)"*(106). In recent years, several researchers have used the mass index in terms of MI (for characterising the relative body mass but not body composition) in addition to BMI as a measure for relative body weight in athletes (8, 22, 56-58, 106, 134), and they have also suggested that body composition assessments should always be complemented by measuring the sitting height (s) for determining the Cormic Index ($C = s/h$) to calculate the MI ($MI_1 = 0.53\ m/(hs)$) as a measure for 'relative body weight' in athletes (1).

Competitive performance and relative body weight.

Figure 27 *"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 when compared to Caucasian White groups* (111). *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* (Figure 23Figure 24), *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:* Figure 22*, 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 6.0 mm). In the female group* (Figure 33)*, 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* (Figure 34) *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.* (112) *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.* (110) *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* (57, 134, 137)*, 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* (57)*: 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”(106).

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 performance class were all between 20 and 35 mm. According to preliminary normative data (86)*, 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)* (58)*, and the eight female athletes of the German National rowing team (U 19) had a median of 70 mm (48 to 79 mm)* (138)*. Compared to the male long-distance runners, the females' D_I-median was about six-times higher, indicating that adipose tissue, which has important endocrine functions* (128)*, 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_I (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_I ($r_s = -0.39$, $p=0.033$).

Seen from a health perspective: “There are no generally accepted optimum values for body weight or percentage of fat mass in different sports…” (1). Data of this and of previous studies (22, 58, 138) *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* (1). *Features of long-distance runners from Kenya* *have previously been analysed by Hamilton* (139). *However, research 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 (1, 5, 107, 140, 141). *The Working Group on Body Composition, Health and Performance, under the auspices of the IOC Medical Commission, has stated* (1)*: "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* (142, 143). *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 later* (144). *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* (8) *and tested within the framework of an international multi-centre study* (22). *This method has also been tested in children* (10)*"*(106).

4.2 Ranges of body fat in female and male elite athletes in various sports.

In this group comprising all elite female and male athletes (Table 20) competing in various sports, the median SAT thickness sum in terms of D_I was about three times higher (72.5 mm vs 24.0 mm) in the female group compared with the male group, whereas the median percentage of embedded fibrous structures in the SAT was lower in females (8.7 %) than males (21.1 %). Compared with the widely-used skinfold technique, the standardised US measurement method allows quantifying the amount of embedded fibrous structures in the SAT thicknesses (6-8, 22). However, to date only preliminary data sets including fibrous structures in the SAT sums have been published (86) for adult athletes and non-athletes. Future studies are needed to determine the relevance of different amounts of embedded fibrous structures in the SAT values. When comparing significant differences in D_I between female and male athletes competing in the same sport, the highest ratios of the median D_I were found in long-distance runners (57.6 mm/8.6 mm = 6.7), followed by badminton players (73.8 mm/21.9 mm = 3.4). When comparing fat patterning between females (N=103) and males (N=163) of all individual eight body sites (excluding heavy weight categories), there were significant differences ($p < 0.01$). The highest ratio was at the LT body site (21.4/3.9 = 5.5), which was around the anthropometric measurement, namely the gluteal (hip) girth, while the lowest ratio was at the LA site (12.7/6.0 = 2.1), followed by ES (5.0/2.6 = 2.3), and UA (6.9/2.8 = 2.5). These sites were drawn (landmarking before US imaging) in the vicinity of the anthropometric measurement waist circumference. Since Vague (145), it is well known that …*"subcutaneous fat distribution is one of the main morphological features of sexual differentiation" (145)*. Therefore, due to this fact results of females and males have to be presented and interpreted separately. The protocol for measuring SAT at eight standardised body sites can also be used to compare trunk-to-extremities ratios of female and male athletes separated by sports. Analyses of females (N=103) and males (N=163), show significant differences in trunk-to-extremities ratios between sexes ($Z = -9.587$, $p<0.01$). The median trunk-to-extremities ratio in females was 0.59 (IQR = 0.27), and in males 1.02 (IQR = 0.67), indicating that males carry higher SAT amounts on the trunk. No significant differences between trunk-to-extremities ratios in females or males separated by sports were analysed. As a reference method for assessing FM and FFM, the multi-component model is known to be time-consuming (42). Therefore, in practice, time-effective, and inexpensive approaches (e.g., surface anthropometry) are commonly used to record differences between sexes (24).

4.2.1 Anthropometry of groups of sports.

Here, in addition to the recently standardised US measurement method for measuring SAT thicknesses, a standardised protocol for measuring circumferences in female and male elite athletes according to the ISAK and IASMS protocol was used. Statistically significant differences were observed between females competing in different sports (Table 18), as well as in males (Table 19). For example, regarding anthropometric parameters, female long-distance runners presented lower waist circumferences than athletes competing in judo and hockey. Further, the biceps circumference (flexed and tensed) was lower in female long-distance runners than in athletes competing in field hockey, and judo. The gluteal (hip) girth was lower in long-distance runners than in females competing in ultimate frisbee, and hockey. The recently introduced thigh girth measurement (according to the IASMS protocol) was lower in long-distance runners than in judokas, ultimate frisbee, hockey, and badminton players. Larsen hypothesised in a review entitled ‘Kenyan dominance in distance running’ *“…that the superior running economy of the Kenyan runners is primarily due to the fact that they have slender limbs with low masses allowing them to run with a minimal energy used for swinging the limbs” (146).*

4.2.2 Subcutaneous adipose tissue in elite athletes.

Compared to other sports, female rowers of the German national team (U19) had D_I medians of 70 mm (48 to 79 mm) (138), international-competing triathletes in this study had D_I medians of 43.4 mm (32.7 to 67.3 mm), and female athletes competing in orienteering had D_I medians of 56.4 mm (52.2 to 65.0 mm). Here, out of 103 adult elite female athletes, two athletes had ‘extremely low’ D_I values, one judoka with D_I 8.8 mm (BMI = 19.2 kg m^{-2}, MI_1 = 19.4 kg m^{-2}), and one long-distance runner (D_I = 20.2 mm (BMI = 18.4 kg m^{-2}, MI_1 = 19.3 kg m^{-2})). When using MI_1 to classify the relative body weight, both females were in normal range according to the WHO (54). Comparing preliminary published data sets (86) with SAT thicknesses of female elite athletes measured in this study more than the half (53%) of all females had ‘considerable ballast weight’, including females competing in ‘weight-sensitive sports’. Before discussing possible optimisation strategies to reduce ‘ballast mass’ in athletes with higher fat amounts, other health and performance parameters have to be considered for avoiding unhealthy weight loss practices (1, 116). Therefore, female athletes and their coaches as well as the whole support staff should pay careful attention to other health parameters and achieving a balance between energy intake and expenditure.

In the male group (N=163), 39 athletes (24 %) had ‘extremely low’ SAT thickness sums D_I, 25 male athletes had ‘very low’, 46 athletes had ‘low’ D_I values, 31 athletes had ‘noticeable ballast weight’, and 22 male athletes (13 %) had ‘considerable ballast weight’. Compared to other sports, male rowers of the German national team (U19) had D_I medians of 26 mm (16 to 55 mm) (138), triathletes in this study had D_I medians of 18 mm (5 to 33 mm), male athletes competing in orienteering had D_I medians of 25 mm (5 to 38 mm), Kenyan runners (discussed above) had 9 mm (3 to 36 mm). The ‘extremely low’ D_I values of Kenyan long-distance runners show significant differences ($p < 0.05$) compared with judokas, badminton players, boxers, hockey players, ultimate frisbee players, and shooters. ‘Very low’ D_I medians were measured in triathletes (D_I median = 18 mm), and ‘low’ D_I medians were recorded in male athletes competing in orienteering (D_I median = 25 mm). Low body weight and body fat may contribute to enhance performance. However, the relationship between competitive success and body fat values or relative body weights may vary in weight-sensitive sports. Keay, Francis, and Hind (147) showed in their study that percentage body fat (using DXA) was not significantly linked to cycling performance. In this study, the authors used an athletic-specific questionnaire and clinical interview (SEAQ-I) to identify low eating availability (low EA) and the possible link to reduced lumbar spine bone mass density (BMD). *“Those cyclists with chronic low EA, also had reduced testosterone, lower body fat and impaired cycling performance at higher training loads”* (147). Therefore, highly-trained athletes may benefit from well-educated support staff to enhance performance and maintain long-term health. The use of accurate (valid), and reliable measurement methods including a standardised protocol for monitoring body composition in elite athletes may support this path within an individual sports career.

5 Conclusions

Despite a nearly 60-year history of ultrasound being used to measure subcutaneous adipose tissue, US was used much less than other methods described in this thesis, although the high accuracy and reliability demands necessary when investigating highly-trained athletes are not reached by any of these other methods. Currently, only preliminary normative data sets for adult athletes and for non-athletes are available (86); results obtained with top level athletes within the framework of this thesis will contribute to an extended reference data base that will be important to enhance the value of this accurate (8, 22), reliable (9, 10), and valid method for measuring SAT thickness layers in athletes to analyse their fat amounts on the fine scale necessary in elite sports. This study highlights the importance of monitoring body fat, here represented as thickness sums of the US measurements - in terms of D_I, D_E, and the fat patterning represented by the eight standardised measurement sites.

In the various groups of athletes investigated here, the applied US method resulted in measurements of SAT thickness sums ranging from values as low as 3 mm (i.e. less than 0.4 mm on average at individual sites) to values as high as 145 mm (i.e. 18 mm on average at individual sites). The method can easily be applied to extremely thin athletes and also to those who have thick layers of subcutaneous body fat as can be found in some sports. The method is easily applicable in both the laboratory and the field when measurers are trained appropriately.

The US measurement results obtained in this group of international-competing elite female (N=105) and male (N=167) athletes from eleven different sports (Table 20) showed that the median D_I was about three times higher (72.5 mm vs 24.0 mm) in females compared with males, whereas the median percentage of embedded fibrous structures in the SAT was lower in females (8.7%) than males (21.1%).

This thesis includes the largest set of US measurements of SAT in elite athletes ever collected. Sums of SAT thicknesses and fat patterning in 272 athletes of eleven sports showed that female athletes of all groups had a significantly different fat patterning, the most prominent difference was found at lateral thigh (the median of the median ratios was 5.4), and they had significantly more body fat (in terms of D_I and D_E) than their male counterparts: the ratios of the medians $D_{I,female}/D_{I,male}$ ranged from 2.1 to 6.7, and the lowest median found in a female group was 43.4 mm, whereas the lowest value of the male athlete groups was 8.6 mm. Obviously, this indicates that we have to consider substantial physiological differences of female and male athletes. This is already considered in the preliminary normative data (86), but data obtained here indicate that the categories for females should be shifted to higher values because only a very low percentage (2 % of the 103 athletes in Figure 44), of females were found to be in the category 'extremely low', whereas 24 % of the 164 male athletes (Figure 44) were found to be in this category.

In all investigated subgroups (eleven different sports, Table 20), SAT thickness sums (group medians in terms of D_I) were much larger in the female subsets than in their male counterparts. The group medians in females ranged from 43.4 mm in the triathlon group to 91.0 mm in the hockey group. The group medians in males ranged from 8.6 mm in the athletics group (Kenyan long-distance runners) to 89.7 mm in the shooting group. In addition, in all subgroups, the percentage of fibrous structures embedded in the SAT was lower in the female subsets than in the male subsets.

Ranges of subcutaneous fat in the athletics (Kenyan long-distance runners) group:

"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 (86)), 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 (86).

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" (106).

Correlation between body fat and performance in Kenyan runners:

"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" (106).

Relative body mass BMI and MI_1 in Kenyan runners and in judokas:

"Many African ethic groups are known to have longer legs compared to Caucasian persons (111, 148), 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)" (106).

"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%)" (106).

In the group judokas: *"In both the female and the male group, there were no significant correlations between relative body weight and D. These results show that both MI1 and BMI are measures of ponderositv, but not capable to assess body composition in athletes"* (58).

It is of paramount importance to point out that accurate body fat measurements as provided by the US method used here are essential for both performance optimisation in all sports where unnecessary body mass is detrimental to performance and for medical surveillance of athletes in weight sensitive sports where underweight problems, eating disorders, and body composition disturbances are common.

5.1 Limitation and Future Suggestion:

- The investigated two main groups of elite athletes - judoka and Kenyan long distance runners - are large when considering the limited number of top level athletes; however, the number of available female Kenyan long distance runners was low and the results obtained with this subgroup should therefore be interpreted with caution. This holds also true for some of the subgroups of the third group of investigated athletes: national and international level athletes of various sports investigated within the framework of the LSA (Leistungssport Austria, High Performance Center).
- US measures subcutaneous adipose tissue, which is known to be the main fat depot in humans, but fat contained in other storages (e.g., intra-abdominal) is not included.
- Marking, US image capturing, and computer-aided quantititative image evaluation takes some time: about 20 to 30 minutes over-all, depending on the experience of the measurer.
- Training of the measurers is necessary to obtain the high accuracy and reliability that is possible with this method (22).
- This study presents SAT thickness values measured at eight standardised body sites in mm, but does not estimate SAT fat mass in kg based on these US measurements; this will be possible with a new version of the software, which was not available when the data were collected for this thesis.
- This study does not include analyses of the medical status of the athletes. Studies that combine accurate and reliable measurements of body fat by means of US combined with medical investigations of the health status are urgently needed to figure out whether minimum body fat values can be established that can be used as a criterion for ‘raising the alarm’ (in combination with the improved measure MI for relative body weight) to prevent severe medical problems in weight sensitive sports.

6 Bibliography

cited in text

(1) Sundgot-Borgen J, Meyer NL, Lohman TG, Ackland TR, Maughan RJ, Stewart AD, 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(16):1012-22.

(2) Ackland TR, Lohman TG, Sundgot-Borgen J, Maughan RJ, Meyer NL, Stewart AD, 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(3):227-49.

(3) Wells KR, Jeacocke NA, Appaneal R, Smith HD, Vlahovich N, Burke LM, et al. The Australian Institute of Sport (AIS) and National Eating Disorders Collaboration (NEDC) position statement on disordered eating in high performance sport. Br J Sports Med. 2020.

(4) Meyer NL, Sundgot-Borgen J, Lohman TG, Ackland TR, Stewart AD, Maughan RJ, 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(16):1044-53.

(5) Müller W, Maughan RJ. The need for a novel approach to measure body composition: is ultrasound an answer? Br J Sports Med. 2013;47(16):1001-2.

(6) Müller W, Horn M, Fürhapter-Rieger A, Kainz P, Kröpfl JM, Ackland TR, et al. Body composition in sport: interobserver reliability of a novel ultrasound measure of subcutaneous fat tissue. Br J Sports Med. 2013;47(16):1036-43.

(7) Müller W, Horn M, Fürhapter-Rieger A, Kainz P, Kröpfl JM, Maughan RJ, 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(16):1028-35.

(8) Müller W, Lohman TG, Stewart AD, Maughan RJ, Meyer NL, Sardinha LB, 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(1):45-54.

(9) Störchle P, Müller W, Sengeis M, Ahammer H, Fürhapter-Rieger A, Bachl N, 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(2):427-38.

(10) Kelso A, Müller W, Fürhapter-Rieger A, Sengeis M, Ahammer H, Steinacker JM. High inter-observer reliability in standardized ultrasound measurements of subcutaneous adipose tissue in children aged three to six years. BMC pediatrics. 2020;20(1):145.

(11) Wang ZM, Pierson RN, Jr., Heymsfield SB. The five-level model: a new approach to organizing body-composition research. Am J Clin Nutr. 1992;56(1):19-28.

(12) Wang ZM, Heymsfield SB, Pi-Sunyer FX, Gallagher D, Pierson RN, Jr. Body composition analysis: Cellular level modeling of body component ratios. Int J Body Compos Res. 2008;6(4):173-84.

(13) Heymsfield SB, Wang Z, Baumgartner RN, Ross R. Human body composition: advances in models and methods. Annu Rev Nutr. 1997;17:527-58.

(14) Snyder WS, Cook MJ, Nasset ES, Karhausen LR, Howells GP, Tipton IH. Report of the task group on Reference Man. Oxford; 1984. Report No.: 23.

(15) Mattsson S, Thomas BJ. Development of methods for body composition studies. Phys Med Biol. 2006;51(13):R203-28.

(16) Shen W, St-Onge MP, Wang ZM, Heymsfield SB. Study of Body Composition: An Overview. In: Heymsfield SB, Lohman TG, Wang ZM, Going SB, editors. Human Body Composition. 2nd ed. United States of America: Human Kinetics; 2005. p. 3-14.

(17) Bea JW, Cureton K, Lee V, Milliken LA. Body Composition Models and Reference Methods. In: Lohman TG, Milliken LA, editors. ACSM`s Body Composition Assessment / American College of Sports. 1st ed: Human Kinetics Publishers; 2019. p. 17-30.

(18) Wajchenberg BL. Subcutaneous and visceral adipose tissue: their relation to the metabolic syndrome. Endocrine reviews. 2000;21(6):697-738.

(19) Suchacki KJ, Tavares AAS, Mattiucci D, Scheller EL, Papanastasiou G, Gray C, et al. Bone marrow adipose tissue is a unique adipose subtype with distinct roles in glucose homeostasis. Nat Commun. 2020;11(1):3097.

(20) Ibrahim MM. Subcutaneous and visceral adipose tissue: structural and functional differences. Obes Rev. 2010;11(1):11-8.

(21) Wang J, Thornton JC, Kolesnik S, Pierson RN, Jr. Anthropometry in body composition. An overview. Ann N Y Acad Sci. 2000;904:317-26.

(22) Müller W, Fürhapter-Rieger A, Ahammer H, Lohman TG, Meyer NL, Sardinha LB, 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. 2021;50(3):597-614.

(23) Bellisari A, Roche AF. Anthropometry and Ultrasound. In: Heymsfield SB, Lohman TG, Wang ZM, Going SB, editors. Human Body Composition. 2th ed: Human Kinetics; 2005. p. 109-27.

(24) Hume P, Sheerin KP, Hans de Ridder J. Non-imaging Method: Surface Anthropometry. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer Nature Singapore; 2018. p. 61-70.

(25) Shaw G, Kerr A. Non-imaging Method: Air Displacement Plethysmography (Bod Pod). In: Hume PA, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer Nature Singapore; 2018. p. 87-99.

(26) Njoku CO, Stewart AD, Hume P, Kolose S. Non-imaging Method: 3D Scanning. In: Hume P, Kerr A, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singaporte: Springer Nature; 2018. p. 71-85.

(27) Stewart AD, Marfell-Jones M, Olds T, Deridder H. International standards for anthropometric assessment. Lower Hutt, New Zealand: International Society for the Advancement of Kinanthropometry; 2011.

(28) Störchle P, Müller W, Sengeis M, Lackner S, Holasek S, Fürhapter-Rieger A. Measurement of mean subcutaneous fat thickness: eight standardised ultrasound sites compared to 216 randomly selected sites. Scientific reports. 2018;8(1):16268.

(29) Wang ZM, Shen W, Withers RT, Heymsfield SB. Multicomponent Molecular-Level Models of Body Composition Analysis. In: Heymsfield SB, Lohman TG, Wang Z, Going SB, editors. Human Body Composition. 2nd ed. United States: Human Kinetics; 2005. p. 163-76.

(30) Behnke ARJ, Feen BG, W. C. Welham WC. THE SPECIFIC GRAVITY OF HEALTHY MEN: BODY WEIGHT ÷ VOLUME AS AN INDEX OF OBESITY. Obesity Research. 1995;3(3):295-300.

(31) Ellis KJ. Human body composition: in vivo methods. Physiol Rev. 2000;80(2):649-80.

(32) Siri WE. Body composition from fluid spaces and density: analysis of methods. In: Brozek J, Henschel A, editors. Techniques for Measuring Body Composition. Washington, DC: National Academy of Sciences; 1961. p. 223-44.

(33) Withers RT, Smith DA, Chatterton BE, Schultz CG, Gaffney RD. A comparison of four methods of estimating the body composition of male endurance athletes. Eur J Clin Nutr. 1992;46(11):773-84.

(34) Andreoli A, Melchiorri G, Volpe SL, Sardella F, Iacopino L, De Lorenzo A. Multicompartment model to assess body composition in professional water polo players. J Sports Med Phys Fitness. 2004;44(1):38-43.

(35) Wang Z, Pi-Sunyer FX, Kotler DP, Wielopolski L, Withers RT, Pierson RN, Jr., et al. Multicomponent methods: evaluation of new and traditional soft tissue mineral models by in vivo neutron activation analysis. Am J Clin Nutr. 2002;76(5):968-74.

(36) Brozek J, Grande F, Anderson JT, Keys A. Densitometric Analysis of Body Composition: Revision of Some Quantitative Assumptions. Ann N Y Acad Sci. 1963;110:113-40.

(37) Selinger A. The Body as a Three Component System: University of Illinois at Urbana-Champaign.; 1977.

(38) Santos DA, Silva AM, Matias CN, Fields DA, Heymsfield SB, Sardinha LB. Accuracy of DXA in estimating body composition changes in elite athletes using a four compartment model as the reference method. Nutr Metab (Lond). 2010;7:22.

(39) Rolland C. Laboratory Methods of Body Composition Analysis. In: Stewart AD, Sutton L, editors. Body Composition in Sport, Exercise and Health. 1st ed. Great Britain: Routledge; 2012. p. 20-41.

(40) Borga M, West J, Bell JD, Harvey NC, Romu T, Heymsfield SB, et al. Advanced body composition assessment: from body mass index to body composition profiling. J Investig Med. 2018;66(5):1-9.

(41) Lohman TG, Milliken LA, Sardinha LB. Introduction to Body Composition and Assessment. In: Lohman TG, Milliken LA, editors. ACSM's Body Composition Assessment. United States: Human Kinetics; 2020. p. 1-15.

(42) Slater G, Shaw G, Kerr A. Athlete Considerations for Physique Measurement. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Springer Nature Singapore: Springer; 2018. p. 47-60.

(43) Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med. 1998;26(4):217-38.

(44) Hume P, Kerr D, Ackland TR. Best Practice Protocols for Physique Assessment in Sport. 1 ed: Springer Singapore; 2018. 276 p.

(45) Ramirez ME. Measurement of subcutaneous adipose tissue using ultrasound images. Am J Phys Anthropol. 1992;89(3):347-57.

(46) Marfell-Jones M, Nevill AM, Stewart AD. Anthropometric Surrogates for Fatness and Health. In: Stewart AD, Sutton L, editors. Body Composition in Sport, Exercise and Health. Abingdon: Routledge; 2012. p. 126-46.

(47) Toomey C, McCreesh K, Leahy S, Jakeman P. Technical considerations for accurate measurement of subcutaneous adipose tissue thickness using B-mode ultrasound. Ultrasound. 2011;19(2):91-6.

(48) Moore TL, Lunt M, McManus B, Anderson ME, Herrick AL. Seventeen-point dermal ultrasound scoring system--a reliable measure of skin thickness in patients with systemic sclerosis. Rheumatology (Oxford). 2003;42(12):1559-63.

(49) Störchle P. Ultrasound Measurement of Subcutaneous Adipose Tissue Thickness: Methodical Improvements, Intra-Observer Reliability in Overweight and Obese Persons, and Fat Patterning Analyses. Graz: Medical University of Graz; 2019.

(50) Brandon LJ, Milliken LA, Blew RM, Lohman T. Body Composition Field Methods. In: Lohman TG, Milliken LA, editors. ACSM's Body Composition Assessment. United States of America: Human Kinetics; 2020. p. 59-89.

(51) Toomey CM, Cremona A, Hughes K, Norton C, Jakeman P. A review of body composition measurement in the assessment of health. Topics in clinical nutrition. 2015;30(1):16-32.

(52) Kagawa M. Anthropometry and Health for Sport. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer; 2018. p. 11-25.

(53) Gallagher D, Heymsfield SB, Heo M, Jebb SA, Murgatroyd PR, Sakamoto Y. Healthy percentage body fat ranges: an approach for developing guidelines based on body mass index. Am J Clin Nutr. 2000;72(3):694-701.

(54) World Health Organization (WHO). Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee. World Health Organization technical report series. 1995b;854:329.

(55) World Health Organization (WHO). Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee. 1995a. Report No.: 0512-3054 (Print)
0512-3054.

(56) Müller W. Determinants of Ski-Jump Performance and Implications for Health, Safety and Fairness. Sports Medicine. 2009;39(2):85-106.

(57) Müller W, Gröschl W, Müller R, Sudi K. Underweight in ski jumping: The solution of the problem. Int J Sports Med. 2006;27(11):926-34.

(58) Sengeis M, Müller W, Störchle P, Führhapter-Rieger A. Body weight and subcutaneous fat patterning in elite judokas. Scand J Med Sci Sports. 2019;29(11):1774-88.

(59) Lackner S, Mörkl S, Müller W, Fürhapter-Rieger A, Oberascher A, Lehofer M, 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. Clinical nutrition (Edinburgh, Scotland). 2019;38(6):2913-21.

(60) Santos DA, Silva AM, Matias CN, Magalhaes JP, Minderico CS, Thomas DM, et al. Utility of novel body indices in predicting fat mass in elite athletes. Nutrition (Burbank, Los Angeles County, Calif). 2015;31(7-8):948-54.

(61) Lennie SC, Amofa-Diatuo T, Nevill A, Stewart AD. Protocol variations in arm position influence the magnitude of waist girth. J Sports Sci. 2013;31(12):1353-8.

(62) Hume PA, Stewart AD. Physique Assessment in Youth Sports for Talent Identification and Development. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer Nature Singapore; 2018. p. 3-10.

(63) Slater G, O’Connor H, Kerr A. Optimising Physique for Sports Performance. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport: Springer Nature Singapore; 2018. p. 27-36.

(64) Kerr A, Hume PA. Non-imaging Method: Bioelectrical Impedance Analysis. In: Hume P, Kerr A, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singaporte: Springer Nature; 2018. p. 101-16.

(65) Moon JR. Body composition in athletes and sports nutrition: an examination of the bioimpedance analysis technique. Eur J Clin Nutr. 2013;67 Suppl 1:S54-9.

(66) Norgan NG. Laboratory and field measurements of body composition. Public Health Nutr. 2005;8(7A):1108-22.

(67) Kyle UG, Bosaeus I, De Lorenzo AD, Deurenberg P, Elia M, Gomez JM, et al. Bioelectrical impedance analysis--part I: review of principles and methods. Clinical nutrition (Edinburgh, Scotland). 2004;23(5):1226-43.

(68) Kyle UG, Bosaeus I, De Lorenzo AD, Deurenberg P, Elia M, Manuel Gomez J, et al. Bioelectrical impedance analysis-part II: utilization in clinical practice. Clinical nutrition (Edinburgh, Scotland). 2004;23(6):1430-53.

(69) Behnke AR, Jr., Feen BG, Welham WC. The specific gravity of healthy men. Body weight divided by volume as an index of obesity. 1942. Obes Res. 1995;3(3):295-300.

(70) Going SB. Hydrodensitometry and Air Displacement Plethysmography. In: Heymsfield SB, Lohman TG, Wang ZM, Going SB, editors. Human Body Composition. 2nd ed. United States of America: Human Kinetics; 2005. p. 17-33.

(71) Siri WE. The gross composition of the body. Adv Biol Med Phys. 1956;4:239-80.

(72) Friedl KE, DeLuca JP, Marchitelli LJ, Vogel JA. Reliability of body-fat estimations from a four-compartment model by using density, body water, and bone mineral measurements. Am J Clin Nutr. 1992;55(4):764-70.

(73) Blew RM, Sardinha LB, Milliken LA. Body Composition Laboratory Methods. In: Lohman TG, Milliken LA, editors. ACSM's Body Composition Assessment. United States: Human Kinetics; 2020. p. 31-58.

(74) Clasey JL, Kanaley JA, Wideman L, Heymsfield SB, Teates CD, Gutgesell ME, et al. Validity of methods of body composition assessment in young and older men and women. J Appl Physiol (1985). 1999;86(5):1728-38.

(75) van Marken Lichtenbelt WD, Hartgens F, Vollaard NB, Ebbing S, Kuipers H. Body composition changes in bodybuilders: a method comparison. Med Sci Sports Exerc. 2004;36(3):490-7.

(76) Dempster P, Aitkens S. A new air displacement method for the determination of human body composition. Med Sci Sports Exerc. 1995;27(12):1692-7.

(77) Kerr A, Slater GJ, Byrne N. Impact of food and fluid intake on technical and biological measurement error in body composition assessment methods in athletes. Br J Nutr. 2017;117(4):591-601.

(78) Slater G, Nana A, Kerr A. Imaging Method: Dual-Energy X-Ray Absporptiometry. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer Nature Singapore; 2018. p. 153-67.

(79) Glüer CC. 30years of DXA technology innovations. Bone. 2017;104:7-12.

(80) Shepherd JA, Ng BK, Sommer MJ, Heymsfield SB. Body composition by DXA. Bone. 2017;104:101-5.

(81) Van Der Ploeg GE, Withers RT, Laforgia J. Percent body fat via DEXA: comparison with a four-compartment model. J Appl Physiol (1985). 2003;94(2):499-506.

(82) Nana A, Slater GJ, Hopkins WG, Halson SL, Martin DT, West NP, et al. Importance of Standardized DXA Protocol for Assessing Physique Changes in Athletes. Int J Sport Nutr Exerc Metab. 2016;26(3):259-67.

(83) Nana A, Slater GJ, Hopkins WG, Burke LM. Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people. Med Sci Sports Exerc. 2012;44(1):180-9.

(84) Kerr A, Slater GJ, Byrne N, Nana A. Reliability of 2 Different Positioning Protocols for Dual-Energy X-ray Absorptiometry Measurement of Body Composition in Healthy Adults. J Clin Densitom. 2016;19(3):282-9.

(85) Herman IP. Sound, Speech, and Hearing. In: Herman IP, editor. Physics of the Human Body. 2nd ed. Switzerland: Springer International; 2016. p. 657-730.

(86) Ackland TR, Müller W. Imaging Method: Ultrasound. In: Hume PA, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer 2018. p. 131-41.

(87) Bazzocchi A, Filonzi G, Ponti F, Albisinni U, Guglielmi G, Battista G. Ultrasound: Which role in body composition? Eur J Radiol. 2016;85(8):1469-80.

(88) Shen W, Wang Z, Punyanita M, Lei J, Sinav A, Kral JG, et al. Adipose tissue quantification by imaging methods: a proposed classification. Obes Res. 2003;11(1):5-16.

(89) Thomas EL, Fitzpatrick JA, Malik SJ, Taylor-Robinson SD, Bell JD. Whole body fat: content and distribution. Prog Nucl Magn Reson Spectrosc. 2013;73:56-80.

(90) Kristen L, MacKenzie-Shalders KL. Imaging Method: Computed Tomography and Magnetic Resonace Imaging. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer Nature Singapore; 2018. p. 143-52.

(91) Ross R, Leger L, Morris D, de Guise J, Guardo R. Quantification of adipose tissue by MRI: relationship with anthropometric variables. J Appl Physiol (1985). 1992;72(2):787-95.

(92) Abate N, Burns D, Peshock RM, Garg A, Grundy SM. Estimation of adipose tissue mass by magnetic resonance imaging: validation against dissection in human cadavers. J Lipid Res. 1994;35(8):1490-6.

(93) Abate N, Garg A, Coleman R, Grundy SM, Peshock RM. Prediction of total subcutaneous abdominal, intraperitoneal, and retroperitoneal adipose tissue masses in men by a single axial magnetic resonance imaging slice. Am J Clin Nutr. 1997;65(2):403-8.

(94) Peng Q, McColl RW, Ding Y, Wang J, Chia JM, Weatherall PT. Automated method for accurate abdominal fat quantification on water-saturated magnetic resonance images. J Magn Reson Imaging. 2007;26(3):738-46.

(95) Stewart AD, Sutton L. Body Composition in Sport, Exercise and Health. 1 ed. London and New York: Routledge; 2012. 218 p.

(96) Carter LJE, Stewart AD. Physique: Phenotype, Somatotype and 3D Scanning. In: Stewart AD, Sutton L, editors. Body Composition in Sport, Exercise and Health. London and New York: Routledge; 2012. p. 64-86.

(97) Moller R, Tafeit E, Pieber TR, Sudi K, Reibnegger G. Measurement of subcutaneous adipose tissue topography (SAT-Top) by means of a new optical device, LIPOMETER, and the evaluation of standard factor coefficients in healthy subjects. Am J Hum Biol. 2000;12(2):231-9.

(98) Jurimae T, Sudi K, Jurimae J, Payerl D, Moller R, Tafeit E. Validity of optical device lipometer and bioelectric impedance analysis for body fat assessment in men and women. Coll Antropol. 2005;29(2):499-502.

(99) Schoeller DA. Hydrometry. In: Heymsfield SB, Lohman TG, Wang Z, Going SB, editors. Human Body Composition. 2nd ed. United States: Human Kinetics; 2005. p. 35-49.

(100) Hollings SC, Hume P. Training and Accreditation Systems and Ethical Considerations. In: Hume P, Kerr DA, Ackland TR, editors. Best Practice Protocols for Physique Assessment in Sport. Singapore: Springer Nature Singapore; 2018. p. 231-41.

(101) Lee V, Brandon LJ, Lohman TG. Assessing Measurement Error. In: Lohman TG, Milliken LA, editors. ACSM's Body Composition Assessment. United States: Human Kinetics; 2020. p. 91-101.

(102) Goncalves EM, Matias CN, Santos DA, Sardinha LB, Silva AM. Assessment of total body water and its compartments in elite judo athletes: comparison of bioelectrical impedance spectroscopy with dilution techniques. J Sports Sci. 2015;33(6):634-40.

(103) Graybeal AJ, Moore ML, Cruz MR, Tinsley GM. Body Composition Assessment in Male and Female Bodybuilders: A 4-Compartment Model Comparison of Dual-Energy X-Ray Absorptiometry and Impedance-Based Devices. J Strength Cond Res. 2020;34(6):1676-89.

(104) Micklesfield LK, Goedecke JH, Punyanitya M, Wilson KE, Kelly TL. Dual-energy X-ray performs as well as clinical computed tomography for the measurement of visceral fat. Obesity (Silver Spring, Md). 2012;20(5):1109-14.

(105) Kaul S, Rothney MP, Peters DM, Wacker WK, Davis CE, Shapiro MD, et al. Dual-energy X-ray absorptiometry for quantification of visceral fat. Obesity (Silver Spring, Md). 2012;20(6):1313-8.

(106) Sengeis M, Müller W, Störchle P, Fürhapter-Rieger A. Competitive Performance of Kenyan Runners Compared to their Relative Body Weight and Fat. Int J Sports Med. 2020.

(107) Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, Warren MP, et al. American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc. 2007;39(10):1867-82.

(108) Harriss DJ, MacSween A, Atkinson G. Ethical Standards in Sport and Exercise Science Research: 2020 Update. Int J Sports Med. 2019;40(13):813-7.

(109) Lenhard W, Lenhard A. Calculation of Effect Sizes. Retrieved from: Dettelbach (Germany). 2016 [Available from: https://www.psychometrica.de/effect_size.html.

(110) Marc A, Sedeaud A, Guillaume M, Rizk M, Schipman J, Antero-Jacquemin J, et al. Marathon progress: demography, morphology and environment. J Sports Sci. 2014;32(6):524-32.

(111) Larsen HB, Christensen DL, Nolan T, Sondergaard H. Body dimensions, exercise capacity and physical activity level of adolescent Nandi boys in western Kenya. Ann Hum Biol. 2004;31(2):159-73.

(112) Mooses M, Hackney AC. Anthropometrics and Body Composition in East African Runners: Potential Impact on Performance. Int J Sports Physiol Perform. 2017;12(4):422-30.

(113) Billat V, Vitiello D, Palacin F, Correa M, Pycke JR. Race Analysis of the World's Best Female and Male Marathon Runners. Int J Environ Res Public Health. 2020;17(4).

(114) Reale R, Slater G, Burke LM. Individualised dietary strategies for Olympic combat sports: Acute weight loss, recovery and competition nutrition. European journal of sport science. 2017;17(6):727-40.

(115) Artioli GG, Saunders B, Iglesias RT, Franchini E. It is Time to Ban Rapid Weight Loss from Combat Sports. Sports Med. 2016;46(11):1579-84.

(116) Burke LM, Slater GJ, Matthews JJ, Langan-Evans C, Horswill CA. ACSM Expert Consensus Statement on Weight Loss in Weight-Category Sports. Curr Sports Med Rep. 2021;20(4):199-217.

(117) Artioli GG, Gualano B, Franchini E, Scagliusi FB, Takesian M, Fuchs M, et al. Prevalence, magnitude, and methods of rapid weight loss among judo competitors. Med Sci Sports Exerc. 2010;42(3):436-42.

(118) Reale R, Slater G, Cox GR, Dunican IC, Burke LM. The Effect of Water Loading on Acute Weight Loss Following Fluid Restriction in Combat Sports Athletes. Int J Sport Nutr Exerc Metab. 2018;28(6):565-73.

(119) Franchini E, Brito CJ, Artioli GG. Weight loss in combat sports: physiological, psychological and performance effects. J Int Soc Sports Nutr. 2012;9(1):52.

(120) Artioli GG, Saunders B, Iglesias RT, Franchini E. Authors' Reply to Davis: "It is Time to Ban Rapid Weight Loss from Combat Sports". Sports Med. 2017;47(8):1677-81.

(121) Schlecht I, Wiggermann P, Behrens G, Fischer B, Koch M, Freese J, et al. Reproducibility and validity of ultrasound for the measurement of visceral and subcutaneous adipose tissues. Metabolism: clinical and experimental. 2014;63(12):1512-9.

(122) Schmölzer B, Müller W. Individual flight styles in ski jumping: results obtained during Olympic Games competitions. Journal of biomechanics. 2005;38(5):1055-65.

(123) Müller W, Platzer D, Schmölzer B. Dynamics of human flight on skis: improvements in safety and fairness in ski jumping. Journal of biomechanics. 1996;29(8):1061-8.

(124) James LP, Haff GG, Kelly VG, Beckman EM. Towards a Determination of the Physiological Characteristics Distinguishing Successful Mixed Martial Arts Athletes: A Systematic Review of Combat Sport Literature. Sports Med. 2016;46(10):1525-51.

(125) Lee RC, Wang Z, Heo M, Ross R, Janssen I, Heymsfield SB. Total-body skeletal muscle mass: development and cross-validation of anthropometric prediction models. Am J Clin Nutr. 2000;72(3):796-803.

(126) Silva AM, Fields DA, Quiterio AL, Sardinha LB. Are skinfold-based models accurate and suitable for assessing changes in body composition in highly trained athletes? J Strength Cond Res. 2009;23(6):1688-96.

(127) Kasper AM, Langan-Evans C, Hudson JF, Brownlee TE, Harper LD, Naughton RJ, et al. Come Back Skinfolds, All Is Forgiven: A Narrative Review of the Efficacy of Common Body Composition Methods in Applied Sports Practice. Nutrients. 2021;13(4).

(128) Trayhurn P, Beattie JH. Physiological role of adipose tissue: white adipose tissue as an endocrine and secretory organ. Proc Nutr Soc. 2001;60(3):329-39.

(129) Brooks GA, Fahey TD, Baldwin KM. Exercise Physiology: Human Bioenergetics and Its Applications. 4 ed. New York: McGraw-Hill; 2005, p.124-154.

(130) Laufteam run2gether Austria. Running wonderland 2019 [October 5, 2018]. Available from: https://run2gether.com/?portfolio=things-to-know&lang=en#tab-id-3.

(131) Wilber RL, Pitsiladis YP. Kenyan and Ethiopian distance runners: what makes them so good? Int J Sports Physiol Perform. 2012;7(2):92-102.

(132) Burke LM, Close GL, Lundy B, Mooses M, Morton JP, Tenforde AS. 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(4):364-74.

(133) Mountjoy M, Sundgot-Borgen J, Burke L, Ackerman KE, Blauwet C, Constantini N, 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(4):316-31.

(134) 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(13):1013-9.

(135) In. World Health Organisation (Ed.) International statistical classification of diseases and related health problems: 10th revision (ICD-10).5th edition WHO Library Cataloguing-in-Publication Data, Geneva, 2016.

(136) World Health Organization (WHO). Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee.; 1995a.

(137) Müller W. Determinants of ski-jump performance and implications for health, safety and fairness. Sports Med. 2009;39(2):85-106.

(138) Kelso A, Trajer E, Machus K, Treff G, Müller W, Steinacker JM. Assessment of subcutaneous adipose tissue using ultrasound in highly trained junior rowers. European journal of sport science. 2017;17(5):576-85.

(139) Hamilton B. East African running dominance: what is behind it? Br J Sports Med. 2000;34(5):391-4.

(140) Becker AE, Grinspoon SK, Klibanski A, Herzog DB. Eating disorders. The New England journal of medicine. 1999;340(14):1092-8.

(141) Sullivan PF. Mortality in anorexia nervosa. The American journal of psychiatry. 1995;152(7):1073-4.

(142) Martinsen M, Bahr R, Børresen R, Holme I, Pensgaard AM, Sundgot-Borgen J. Preventing eating disorders among young elite athletes: a randomized controlled trial. Medicine & Science in Sports & Exercise. 2014;46(3):435-47.

(143) Martinsen M, Sundgot-Borgen J. Higher prevalence of eating disorders among adolescent elite athletes than controls. Medicine & Science in Sports & Exercise. 2013;45(6):1188-97.

(144) Sundgot-Borgen J, Danielsen KK, Torstveit MK, editors. Female Former Elite Athletes Suffering From Eating Disorders During Their Career. A 15-20 Year Follow-up. Medicine and Science in Sports and Exercise; 2012: Lippincott Williams & Wilkins 530 Walnut St, Philadelphia, PA 19106-3621 USA.

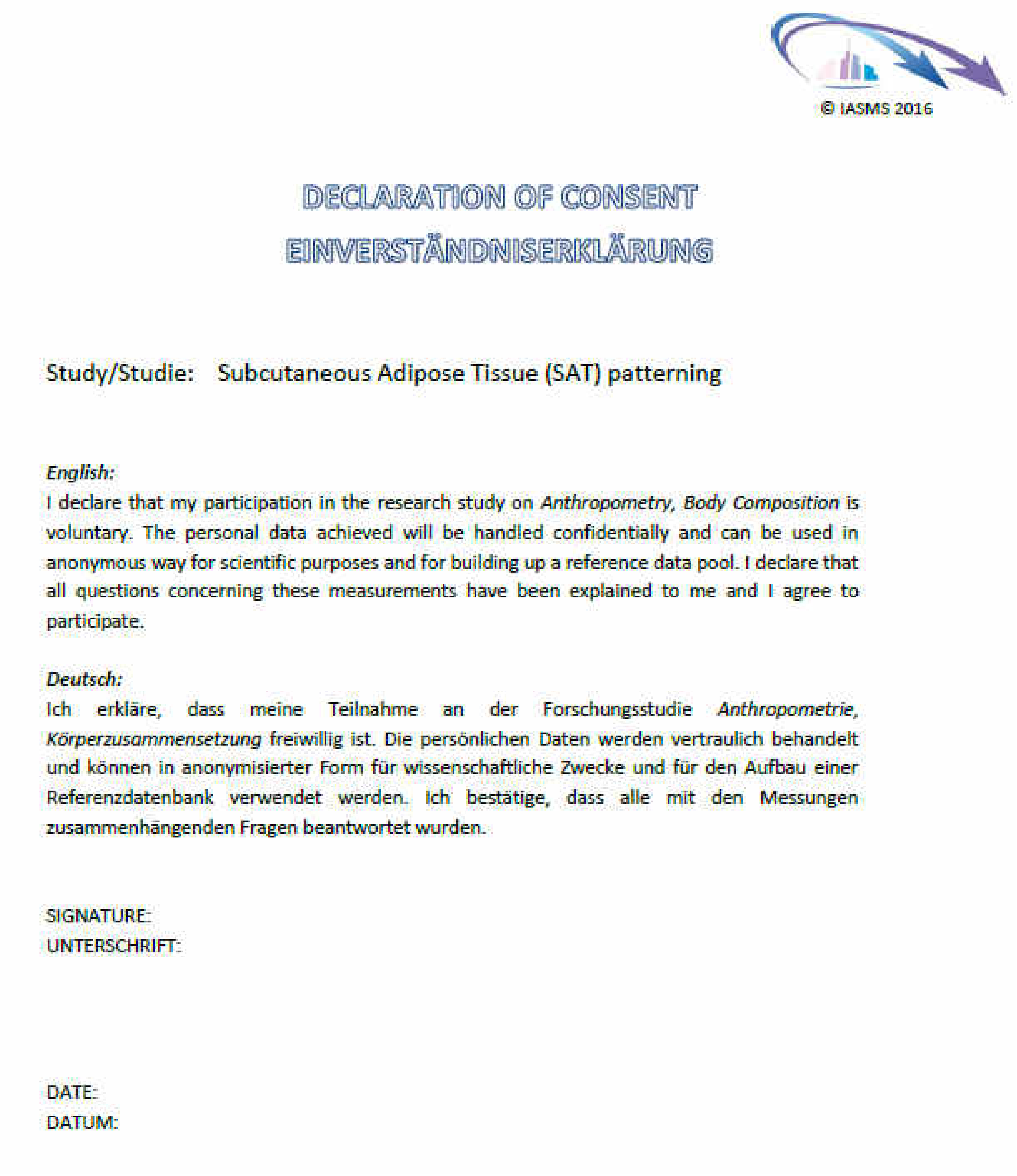
(145) Vague J. Sexual differentiation; Factor determining forms of obesity. Presse Med. 1947;55(30):339.

(146) Larsen HB. Kenyan dominance in distance running. Comp Biochem Physiol A Mol Integr Physiol. 2003;136(1):161-70.

(147) Keay N, Francis G, Hind K. Low energy availability assessed by a sport-specific questionnaire and clinical interview indicative of bone health, endocrine profile and cycling performance in competitive male cyclists. BMJ Open Sport Exerc Med. 2018;4(1):e000424.

(148) Norgan NG. Population differences in body composition in relation to the body mass index. Eur J Clin Nutr. 1994;48 Suppl 3:S10-25; discussion S6-7.

7 Appendix



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DECLARATION OF CONSENT

EINVERSTÄNDNISERKLÄRUNG

Study/Studie: Subcutaneous Adipose Tissue (SAT) patterning

English:

I declare that my participation in the research study on *Anthropometry, Body Composition* is voluntary. The personal data achieved will be handled confidentially and can be used in anonymous way for scientific purposes and for building up a reference data pool. I declare that all questions concerning these measurements have been explained to me and I agree to participate.

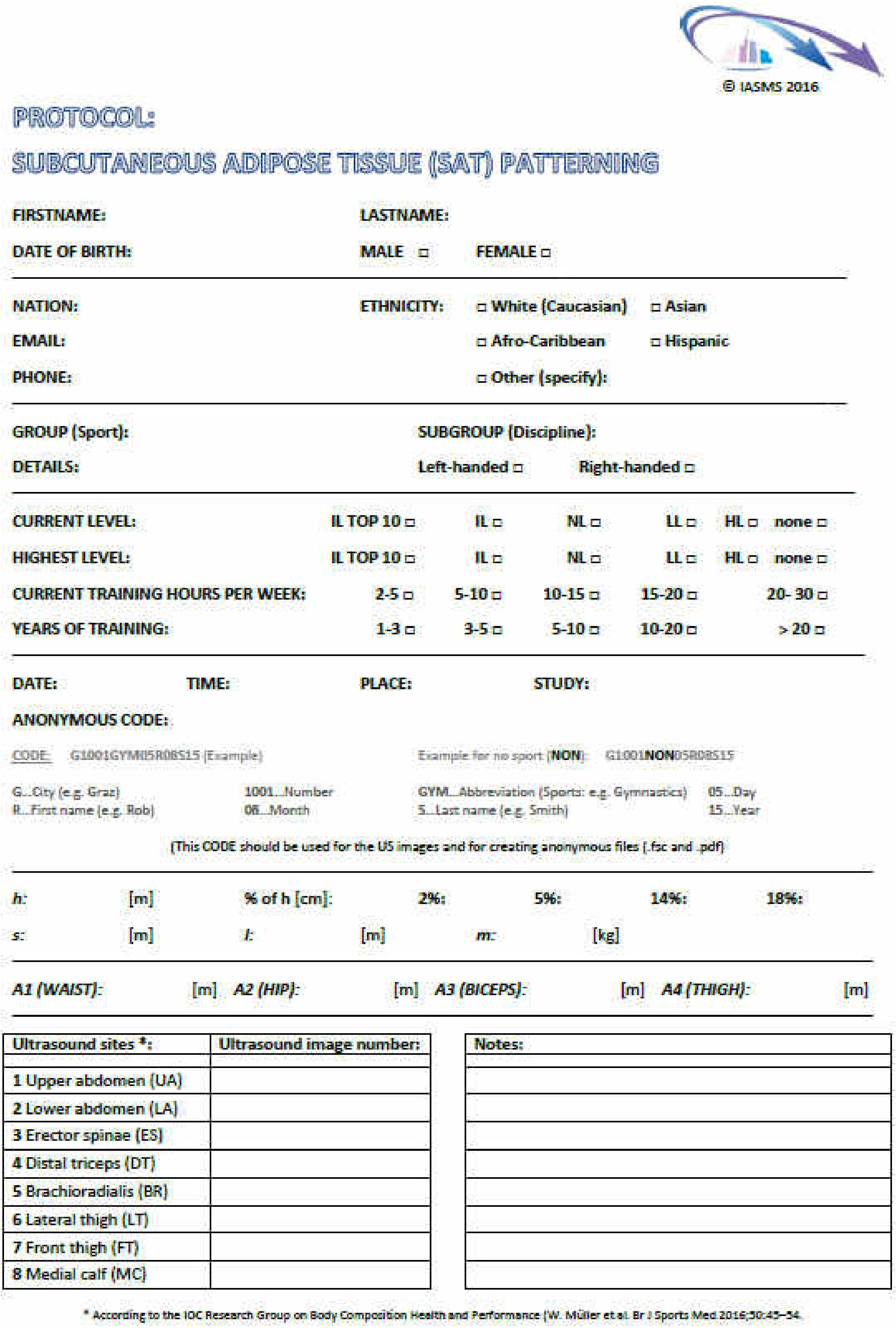
Deutsch:

Ich erkläre, dass meine Teilnahme an der Forschungsstudie *Anthropometrie, Körperzusammensetzung* freiwillig ist. Die persönlichen Daten werden vertraulich behandelt und können in anonymisierter Form für wissenschaftliche Zwecke und für den Aufbau einer Referenzdatenbank verwendet werden. Ich bestätige, dass alle mit den Messungen zusammenhängenden Fragen beantwortet wurden.

SIGNATURE:
UNTERSCHRIFT:

DATE:
DATUM:

Figure 46: Declaration of Consent according to © IASMS, 2016.



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PROTOCOL:

SUBCUTANEOUS ADIPOSE TISSUE (SAT) PATTERNING

FIRSTNAME: **LASTNAME:**

DATE OF BIRTH: **MALE** ☐ **FEMALE** ☐

NATION: **ETHNICITY:** ☐ White (Caucasian) ☐ Asian

EMAIL: ☐ Afro-Caribbean ☐ Hispanic

PHONE: ☐ Other (specify):

GROUP (Sport): **SUBGROUP (Discipline):**

DETAILS: Left-handed ☐ Right-handed ☐

CURRENT LEVEL: IL TOP 10 ☐ IL ☐ NL ☐ LL ☐ HL ☐ none ☐

HIGHEST LEVEL: IL TOP 10 ☐ IL ☐ NL ☐ LL ☐ HL ☐ none ☐

CURRENT TRAINING HOURS PER WEEK: 2-5 ☐ 5-10 ☐ 10-15 ☐ 15-20 ☐ 20- 30 ☐

YEARS OF TRAINING: 1-3 ☐ 3-5 ☐ 5-10 ☐ 10-20 ☐ > 20 ☐

DATE: **TIME:** **PLACE:** **STUDY:**

ANONYMOUS CODE:

CODE: G1001GYM05R08S15 (Example) Example for no sport (**NON**): G1001**NON**05R08S15

G...City (e.g. Graz) 1001...Number GYM...Abbreviation (Sports: e.g. Gymnastics) 05...Day
R...First name (e.g. Rob) 08...Month S...Last name (e.g. Smith) 15...Year

(This CODE should be used for the US images and for creating anonymous files (.fsc and .pdf)

h: [m] % of h [cm]: 2%: 5%: 14%: 18%:

s: [m] *l:* [m] *m:* [kg]

A1 (WAIST): [m] *A2 (HIP):* [m] *A3 (BICEPS):* [m] *A4 (THIGH):* [m]

Ultrasound sites *:	Ultrasound image number:
1 Upper abdomen (UA)	
2 Lower abdomen (LA)	
3 Erector spinae (ES)	
4 Distal triceps (DT)	
5 Brachioradialis (BR)	
6 Lateral thigh (LT)	
7 Front thigh (FT)	
8 Medial calf (MC)	

Notes:

* According to the IOC Research Group on Body Composition Health and Performance (W. Müller et al. Br J Sports Med 2016;50:45–54.

Figure 47: Protocol - SAT Patterning according to © IASMS, 2016.