Bulletin der Schweizerischen Gesellschaft für Anthropologie 17(1–2): 35–44 (2011)
Bulletin de la Société Suisse d'Anthropologie 17(1–2): 35–44 (2011) ISSN 14208-4835

Body Mass and Body Mass Index estimation in medieval Switzerland

Frank Siegmund,[1] Christina Papageorgopoulou[2,3]

[1]*Seminar für Ur- und Frühgeschichte, University of Basel, Switzerland*
[2]*Institute of Anthropology, Group of Paleogenetics, Johannes Gutenberg University, Mainz, Germany*
[3]*Archaeological Service Grisons, Switzerland*

Summary

Body mass (BM) and furthermore body mass index (BMI) are well-known proxies used in medicine as a diagnostic tool to identify weight problems, health risks, and to assess biological standards of living within populations. The prediction of body mass (BM) from skeletal material is still challenging, although many studies have indicated that BM can be estimated from human skeletal remains and results have been acquired from early hominines. The present paper applies BM estimation formulae (Auerbach and Ruff 2004, Grine *et al.* 1995, McHenry 1992, Ruff *et al.* 1991) to skeletal populations from Switzerland (5th–15th c. AD; 291 males, 221 females) with the aim to reconstruct the BM and the BMI within a specific geographical and temporal setting. Correlation between the robusticity of the lower limbs in terms of external bone dimensions with BM and BMI were tested. Parameters such as sex and age were considered. The method of Auerbach and Ruff (2004) offered the most reliable results. The mean body weight and the BMI for males was estimated 71.7 kg (s.d. 6.4) and 26.0 (s.d. 2.3), and for females 59.0 kg (s.d. 5.5) and 24.8 (s.d. 2.3) respectively. External bone dimension were highly correlated to body weight in males and females suggesting the strong correlation between biomechanical loading and long bone shape and size. The BMI was slightly increasing from adult to mature and slightly diminishing afterwards.

Key words: growth, skeletal development, standard of living, bone robusticity

Zusammenfassung

Das Körpergewicht und vor allem der Body Mass Index (BMI) sind bekannte Indikatoren zur Identifizierung von Gewichtsproblemen und Gesundheitsrisiken, dienen aber auch als Schätzer für den Lebensstandard einer Bevölkerung. Aussagen zum Lebendgewicht aufgrund von menschlichen Skelettresten sind schwierig, doch nach Ausweis verschiedener Studien grundsätzlich möglich, wobei die bisherigen Arbeiten vor allem auf frühe Hominiden zielen. Der vorliegende Aufsatz stellt alle gängigen Formeln vor (Auerbach und Ruff 2004, Grine *et al.* 1995, McHenry 1992, Ruff *et al.* 1991) und wendet sie auf mittelalterliche Populationen der Schweiz (5.–15. Jh., 291 Männer, 221 Frauen) an, um Aussagen zum Körpergewicht und zum BMI zu gewinnen. Der Zusammenhang der Robustizität der unteren Extremitäten mit dem rekonstruierten Körpergewicht und BMI wird untersucht, ebenso der Zusammenhang mit dem Geschlecht und Alter der Individuen. Im Vergleich bietet die Schätzmethode nach Auerbach und Ruff (2004) die zuverlässigsten Ergebnisse. Danach lag im Schweizer Mittelalter des mittlere Gewicht der Männer bei 71,7 kg (Std.abw. 6,4), der BMI bei 26,0 (Std.abw. 2,3), das mittlere Gewicht der Frauen bei 59,0 kg (Std.abw. 5,5), ihr BMI bei 24,8 (Std.abw. 2,3). Die Querschnittsmasse der Langknochen sind mit dem Körpergewicht hochsignifikant korreliert, zeigen also einen klaren Zusammenhang mit der gewichtsbedingten mechanischen Belastung der Beine. Der mittlere BMI steigt vom adulten zum maturen Alter deutlich und stagniert danach. Innerhalb des Mittelalters bleibt das mittlere Körpergewicht weitgehend konstant, der BMI nimmt leicht zu.

Schlüsselwörter: Körpergewicht, BMI, Wachstum, Skelettentwicklung, Lebensstandard, Knochenrobustizität

Introduction

Body mass (BM) and furthermore body mass index (BMI) are well-known proxies commonly used by the WHO to classify underweight, overweight and obesity in adults (WHO Global database on BMI). Body mass index (BMI) was invented by the Belgian physician Adolphe Quetelet in 1832 (Eknoyan 2008, Rössner 2007) and is defined as the weight in kilograms divided by the square of the height in meters (kg/m²). Increased BMI values are strongly associated with health problems e.g. cardiovascular diseases, obesity, diabetes and high mortality risks (Foucan *et al.* 2002, Lakoski *et al. in print*, Prospective Studies 2009). However many researchers highlight that BMI values do not represent real adiposity differences, since BMI does not

Tab. 1: Swiss medieval populations used in this study. BM: body mass, mean estimation. BMI: body mass index, with mean estimation of BM and stature after Pearson (1899). n individuals: sexed adults with estimated BM.

Reference	Skeletal series	Canton	Dating c. AD	n ♂	BM ♂	BMI ♂	n ♀	BM ♀	BMI ♀
Trancik Petitpierre, *unpubl.*	Aesch	BL	8.–10.	38	69.9 ±4.7	25.5 ±1.9	23	57.6 ±4.5	24.2 ±1.6
Kauffmann 1989	Güttingen	TG	5.–7.	11	70.7 ±6.6	25.0 ±2.3	4	57.7 ±3.0	24.5 ±1.1
Ulrich-Bochsler 2006	Kallnach 1–2	BE	8.–10.	23	73.8 ±5.2	25.9 ±1.6	17	57.7 ±6.1	23.8 ±1.4
Ulrich-Bochsler 2006	Kallnach 3–4	BE	11.–15.	2	70.5 ±5.2	26.0 ±1.4	6	60.5 ±4.7	26.3 ±2.9
Papageorgopoulou, *unpubl.*	Mistail	GR	11.–15.	8	70,5 ±7.2	25.5 / 1.7	2	54.3 ±4.7	23.2 ±0.7
Trancik-Petitpierre 1991	Oberwil	BL	5.–7.	10	72.5 ±6.6	25.3 ±2.2	9	58.3 ±4.5	24.1 ±1.5
Hauser 1938	Oerlingen	ZG	5.–7.	11	70.5 ±6.9	24.6 ±2.1	10	58.1 ±4.1	22.9 ±1.2
Papageorgopoulou, *unpubl.*	Paspels	GR	11.–15.	1	67.3 -	27.9 -	1	54.2 -	22.9 -
Kaufmann 1987	Pratteln	BL	4.	6	73.1 ±6.0	25.4 ±3.0	1	52.7 -	21.8 -
Kaufmann and Schoch 1983	Ried-Mühlehölzli	FR	5.–7.	17	72.6 ±6.1	25.9 ±1.9	20	59.3 ±4.9	24.0 ±1.8
Ulrich-Bochsler 1988	Rohrbach 1	BE	8.–10.	2	75.3 ±3.7	25.8 ±0.1	-	-	-
Ulrich-Bochsler 1988	Rohrbach 2–3	BE	11.–15.	3	77.9 ±3.4	27.2 ±0.6	1	63.4 -	24.8 -
Ulrich-Bochsler 2009	Seeberg	BE	5.–7.	10	75.0 ±6.5	25.9 ±2.1	6	62.1 ±7.6	25.1 ±3.4
Ulrich-Bochsler and Meyer 1994	Steffisburg	BE	8.–10.	17	72.8 ±6.5	25.1 ±1.5	10	62.2 ±8.5	24.9 ±2.2
Papageorgopoulou, *unpubl.*	Tinizong	GR	11.–15.	5	70.1 ±6.1	26.6 ±2.6	3	62.9 ±5.6	24.9 ±1.7
Papageorgopoulou 2008	Tomils	GR	11.–15.	115	71.4 ±7.3	26.6 ±2.6	103	58.9 ±5.5	25.3 ±2.1
Ulrich-Bochsler and Meyer 1992	Walkringen 1–2	BE	11.–15.	8	71.9 ±3.9	25.7 ±0.7	3	66.8 ±3.4	26.4 ±1.5
Ulrich-Bochsler and Meyer 1992	Walkringen 3–4	BE	11.–15.	4	72.5 ±5.3	25.4 ±1.7	2	59.7 ±0.3	25.1 ±0.1

Tab. 2: BM estimation on Swiss medieval skeletal material (n=512, 291 males and 221 females) applying different methods. ISD: index of sexual dimorphism.

	MALES		FEMALES		
	mean ±st.dev.	min.-max.	mean ±st.dev.	min.-max.	ISD
Ruff *et al.* 1991 [1,2]	71.2 ±6.8	43.3–95.9	61.5 ±5.4	45.6–82.0	0.146
McHenry 1992 [4]	69.5 ±6.2	44.2–92.0	55.5 ±5.5	39.2–76.6	0.171
Grine *et al.* 1995 [5]	74.4 ±6.3	48.7–97.1	60.1 ±5.6	43.6–81.5	0.213
mean estimation [6]	71.7 ±6.4	45.4–95.0	59.0 ±5.5	42.8–80.1	0.194

Tab. 3: Comparison of population means of BMI, when applying different methods for BM estimation and for stature estimation (sexed and adult individuals, 286 males and 208 females).

Method of BM estimation:	Pearson 1899	Trotter/Gleser 1952 'negro'	Trotter/Gleser 1952 'white'	Breitinger 1937 and Bach 1965
♂ Mittel [6]	26.0 ±2.3	26.1 ±2.4	24.8 ±2.3	25.0 ±2.1
♂ Ruff *et al.* [1]	25.8 ±2.4	25.9 ±2.5	24.6 ±2.4	24.9 ±2.2
♂ McHenry [4]	25.2 ±2.2	25.3 ±2.3	24.0 ±2.3	24.3 ±2.0
♂ Grine at al. [5]	27.0 ±2.2	27.1 ±2.4	25.7 ±2.3	26.0 ±2.1
♀ Mittel [6]	24.8 ±2.0	24.6 ±2.1	23.6 ±2.1	23.2 ±1.9
♀ Ruff *et al.* [2]	25.8 ±2.0	25.6 ±2.1	24.6 ±2.1	24.1 ±1.8
♀ McHenry [4]	23.3 ±2.0	23.2 ±2.1	22.2 ±2.1	21.8 ±1.9
♀ Grine *et al.* [5]	25.3 ±2.1	25.1 ±2.2	24.1 ±2.2	23.6 ±1.9

Tab. 4: Correlation (after Pearson) between body mass (mean estimation) and external bone dimensions of the femur.

	MALES		FEMALES	
	n	**corr. / sign.**	**n**	**corr. / sign.**
F6, sagittal midshaft diameter	76	** 0.327 / 0.004	49	** 0.572 / 0.000
F7, transverse midshaft diameter	76	** 0.462 / 0.000	50	** 0.675 / 0.000
F8, midshaft circumference	267	** 0.455 / 0.000	205	** 0.447 / 0.000
F9, transverse upper diaphyseal diameter	278	** 0.486 / 0.000	218	** 0.439 / 0.000
F10, sagittal upper diaphyseal diameter	277	** 0.385 / 0.000	217	** 0.316 / 0.000
robusticity index (F6+F7/F2)	254	0.067 / 0.287	191	0.043 / 0.551

Tab. 5: Correlation (after Pearson) between BMI (BM mean estimation, stature after Pearson 1899) and external bone dimensions of the femur.

	MALES		FEMALES	
	n	**corr. / sign.**	**n**	**corr. / sign.**
F6, sagittal midshaft diameter	75	-0.063 / 0.589	45	0.285 / 0.057
F7, transverse midshaft diameter	75	0.011 / 0.928	46	** 0.488 / 0.001
F8, midshaft circumference	265	-0.026 / 0.679	200	0.120 / 0.090
F9, transverse upper diaphyseal diameter	273	0.090 / 0.137	205	* 0.154 / 0.027
F10, sagittal upper diaphyseal diameter	272	0.027 / 0.663	205	0.064 / 0.358
robusticity index (F6+F7/F2)	222	** 0.259 / 0.000	178	** 0.158 / 0.035

Tab. 6: Changes of body mass BM and body mass index BMI over time in medieval Switzerland. Differences in BM are not significant (Kruskal-Wallis-H-Test: males chi-square 1.024, sign. 0.599; females chi-square 0.671, sign. 0.715). Differences in BMI are significant (Kruskal-Wallis-H-Test: males chi-square 14.105, sign. 0.001; females chi-square 13.711, sign. 0.001).

	MALES			FEMALES		
	n	**BM kg mean ± s.d.**	**BMI mean ± s.d.**	**n**	**BM kg mean ± s.d.**	**BMI mean ± s.d.**
11.–15. c. AD	141	71.2 ±7.0	26.5 ±2.5	114	59.1 ±5.6	25.3 ±2.1
8.–10. c. AD	85	72.0 ±5.4	25.6 ±1.7	57	58.9 ±6.0	24.4 ±1.9
5.–7. c. AD	59	72.3 ±6.5	25.4 ±2.1	49	59.1 ±4.9	24.1 ±1.9

Tab. 7: Body mass and body mass index age differences. Differences of body mass for males slightly significant (Kruskal-Wallis-H-Test: chi-square 7.835, sign. 0.020), for females not significant (chi-square 0.783, sign. 0.676). Differences of BMI not significant (Kruskal-Wallis-H-Test: males chi-square 3.677, sign. 0.159; females chi-square 3.663, sign. 0.160).

	MALES			FEMALES		
	n	**BM kg mean ± s.d.**	**BMI mean ± s.d.**	**n**	**BM kg mean ± s.d.**	**BMI mean ± s.d.**
senile	57	72.5 ±7.1	26.4 ±2.4	42	59.0 ±5.8	24.4 ±1.9
mature	135	72.4 ±6.4	26.1 ±2.4	86	59.6 ±5.4	25.1 ±1.8
adult	78	70.6 ±5.8	25.7 ±1.8	80	58.6 ±5.6	24.8 ±2.4

differentiate fat from muscle mass (Franzosi 2006). This is especially evident if BMI is not standardized for sex, age and ethnicity (Deurenberg *et al.* 2002, Franzosi 2006, Gallagher *et al.* 1996, Rush *et al.* 2007, Sluyter *et al.* 2011).

Most studies on BMI are strongly related to the obesity epidemic in the developed countries, however there is a large body of literature on BMI related to socioeconomic aspects, biological standards of living and diachronic trends (Komlos 2006, Komlos and Brabec 2010, Komlos *et al.* 2009, Komlos and Lauderdale 2007, Rühli *et al.* 2008, Staub *et al.* 2010). Under these aspects, BM and BMI estimations could be used as proxy of assessing health and nutritional status, living conditions and general welfare of past populations.

BM and BMI are easily calculated on modern populations as the required variables, weight and stature, can be easily acquired. On skeletal populations the estimation of BM and furthermore BMI is challenging since BM and stature have to be reconstructed from the skeletal elements. Both for the estimation of stature and BM regressions are used, developed on anthropometric variables – for an overview of the methods see (Siegmund 2010). The estimation of stature, with all limitations, is a routine for any anthropological study and significant literature exists on the best choice and application of the methods (Raxter *et al.* 2006, Siegmund 2010, Vercellotti *et al.* 2009). On the contrary, BM estimations are rarely attempted although several studies have indicated that BM can be estimated from human skeletal remains and results have been acquired from early hominines (Hartwig-Scherer 1994, Kappelman 1996, Rafferty *et al.* 1995, Ruff 2010, Ruff *et al.* 1997). BM and BMI values on post-palaeolithic skeletal remains have hardly been reconstructed (Vančata and Charvátová 2001) with the exception of the Tyrolean Iceman „Ötzi", whose BM was estimated to be 61 kg (Ruff *et al.* 2006).

The BM from skeletal material can be directly inferred from the size of bone elements which support the body weight e.g. femur, calcaneus. It has been shown that bones respond to changes in mechanical loading through alterations in compact cortical and trabecular bone. This variation has been observed on external articular dimensions e.g. femur head diameter, on diaphyseal subperiosteal dimensions and on cross sectional geometry (Ruff 1988, Ruff *et al.* 1991). Diaphyseal subperiosteal geometry combined to cross sectional geometry produce slightly better results (3% error) than articular dimensions (5% error) (Ruff *et al.* 1991), however both methods have been equally used and further developed. In the literature there are four methods for BM estimation using femoral head articular size (Auerbach and Ruff 2004, Grine *et al.* 1995, McHenry 1992, Ruff *et al.* 1991). BM and BMI estimation methods for skeletal material have also been developed using metrical dimensions of other bone elements. Porter reported on a large anthropometric study that the first lumbar vertebra, the combination of the tibial length, the tibial shaft and the width of the ankle provided the most reliable results for BMI estimation from skeletal material (Porter 1999). Wheatley examined the value of bone mineral density (BMD) and bone mineral content (BMC) on the proximal femur for BM estimation by using DXA methods. Although the statistical tests showed a high correlation between the DXA data and the body weight, the BM estimation errors were too high to be of any further use (Wheatley 2005).

Another approach for BM estimation is the use of the bi-iliac breadth / maximum pelvic breadth in association with the stature of the individuals (Auerbach and Ruff 2004, Ruff *et al.* 1997). The method offers the most reliable results compared to the femur external dimensions based methods (Auerbach and Ruff 2004). The advantage of the method is that the data can be easily acquired on living individuals without the need of radiographs (Ruff *et al.* 2005), while the biggest disadvantage is the incomplete preservation of both pelvic elements and the sacrum in most skeletal remains. Additionally the pelvic metrical data are not usually included in the standard anthropological dataset, while on the contrary external dimensions of the femur are standard in most anthropological studies. This gives the possibility to reconstruct the BM on archaeological populations retrospectively and offers more comparable data.

The aim of the present study is to test the available BM estimation formulae based on the femoral head breadth (Auerbach and Ruff 2004, Grine *et al.* 1995, McHenry 1992, Ruff *et al.* 1991) on skeletal populations from medieval Switzerland and to reconstruct the BM and the BMI within a specific temporal and geographical setting. Parameters such as sex, age and robusticity will be considered and diachronic changes and comparisons to pre-industrial BM and BMI data will be attempted.

Material and Methods

The skeletal material used for the present study derives from Swiss archaeological cemeteries dating from the 5th to the 15th c. AD (Tab. 1). The data have mostly been collected from published manuscripts or have been generated by the authors themselves. The collection was restricted to datasets which included the necessary variables for the BM estimation (F18, F19 or F20, after Martin 1914), and only when the metrical data was acquired after the guidelines of Martin (1914, 1928, Martin and Saller 1957) in order to restrict methodological errors. All together the dataset includes 512 adult individuals (291 males and 221 females) from 18 archaeological populations. Age and sex determination of all series were performed after the "complex" method (Acsádi and Nemeskéri 1970, Anthropologists 1980).

For the BM estimation the methods of Ruff *et al.* (1991), McHenry (1992), Grine *et al.* (1995) and Auerbach and Ruff (2004) were used. The method of Ruff *et al.* (1991) used the x-rays of 80 black and white Americans (41 males, 39 females) between the age of 24 and 81 with known weight at the current time (mean weight 76.7 kg) and at the age of 18. The weight was calculated by using regressions inferred both from the current weight and the weight at the age of 18. Two sex-specific and one non-sex-specific formulae were generated.

[1] ♂ kg weight = [(2.741 × mm HDB) - 54.9] × 0.9, with SEE 13.7, %SEE 16.9; r^2 (18 years weight) 0.537, r^2 (current weight) 0.497.

[2] ♀ kg weight = [(2.426 × mm HDB) - 35.1] × 0.9, with SEE 17.5, %SEE 24.1; r^2 (18 years weight) 0.087, r^2 (current weight) 0.411.

[3] ♂/♀ kg weight = [(2.160 × mm HDB) - 24.8] × 0.9, with SEE 15.6, %SEE 20.3; r^2 (18 years weight) 0.508, r^2 (current weight) 0.486.

Ruff *et al.* (1991) tested their formula on a white American population and on Pecos Pueblos and found an error of ±2 % and ±8 % respectively. They suggested that results should be corrected to 90% when applied to archaeological populations in order to balance the tendency of his reference series to increased body fat. Therefore the above formula include the recommended multiplication with a factor of 0.9.

The method of Mc Henry (1992) was aiming to reconstruct the BMI of Hominids, whose BM is significantly lower compared to modern humans. Therefore he used a reference population of 59 small-bodied individuals including North Americans, African Pygmies and Khoisan (weight 30.4–64.9 kg). He used 13 different measurements and developed three different regressions methods with numerous formulae. Recent studies (Auerbach and Ruff 2004, Kurki *et al.* 2010) used his data of small-bodied individuals and generated the following formula:

[4] ♂/♀ kg weight = (2.239 × mm Femur head breadth) - 39.9.

The formula of Grine and colleagues (1995) was developed on large bodied individuals of African American, European American, and Native American origin with a weight of 54–84 kg. The formula is not sex-specific.

[5] ♂/♀ kg weight = (2.268 × mm femur head breadth) - 36.5.

Auerbach and Ruff (2004) compared the three methods with the most accurate bi-iliac breadth method. The method of Ruff *et al.* (1991) underestimated the BM by about 0.15%, the method of Grine *et al.* (1995) overestimated the results by about 1.5% and the method of McHenry (1992) underestimated by about 4.8%. Therefore they proposed that the arithmetic mean of the above methods gives the most reliable results when applied to normal-bodied individuals. The arithmetic mean compared to the bi-iliac breadth method underestimated the BM by about 0.7%. The arithmetic mean should not be applied to very small-bodied or large-bodied individuals because it would overestimate the BM by about 10.7% or underestimate at about 3.6% respectively (Auerbach and Ruff 2004).

[6] Arithmetic mean of [1 or 2 or 3], [4] and [5].

Equivalent to femur breadth diameter used by the above methods is the measurement F19 after Martin (1914); in cases where F19 was not available it was generated from F20 femur head circumference:

[7] F19 = (F20 / 3.14159).

The correlation of BM and BMI to robusticity parameters was calculated in order to test the hypothesis of bone size changes towards mechanical loading for the specific populations. The classical Robusticity Index (RI) after Martin (1914) was used, but further the unstandardized external bone dimensions (F6, F7, F8, F9, F10; see tab. 4–5) were also tested. Previous studies have shown that standardized variables are extremely sensitive to limb length differences (Holliday 2002), differences in bone length between individuals and populations may cause traditional measures of robusticity to differ from those based on estimates of bone strength standardised to BM (Holliday and Franciscus 2009, Stock and Shaw 2007). In addition correlations of RI and BMI can lead to artefacts since RI and BMI are both calculated using the femur length.

The stature was estimated after Pearson (1899) that proved to be the most appropriate method for Swiss and other central European populations in previous studies (Siegmund 2010). However, BMI data based on other popular stature estimation methods was calculated for comparative reasons. The BMI was then calculated as:

[8] BMI = BM in kg / $(\text{stature in m})^2$

The sexual dimorphism index was calculated after the formula of Smith (1999) in order to prove the plausibility of our results in the same way as Kurki *et al.* 2010.

[9] ISD = (males - females) / [(males + females)/2]

All calculations were made using SPSS 19.

Results

The BM for the 291 males and 221 females from the three different methods can be observed on table 2. All long bone dimensions follow a normal distribution as validated by Kolmogorov-Smirnov-tests. Therefore parametric statistics were applied with mean and standard deviation given in the tables. For the males the method of Grine *et al.* (1995) produces the largest values compared to the other methods while the method of McHenry (1982) produces the lowest values (Tab. 2). The method of Ruff *et al.* (1991) and the mean estimation proposed by Auerbach and Ruff (2004) show a difference of 0.5 kg. For the females the method of McHenry (1982) produces the lowest values and the method of Ruff *et al.* (1991) the highest. In this case the method of Grine *et al.* (1995) does not produce the highest values but his estimation falls between the other two methods. The differences between the higher and the lower estimation is 4.9 kg by males and 6.0 kg by females, the index of sexual dimorphism ranges between 0.146 and 0.213. The mean BM for males and females is 71.7 and 59.0 respectively with a high standard deviation; the standard deviation of the four methods is similar.

The robusticity of the femur in terms of external dimensions was significant and in some cases highly correlated to the BM (Tab. 4). For males the upper transverse diaphyseal diameter (F9) exhibited the higher correlation followed by the midshaft transverse diameter (F7) and the circumference (F8), while the sagittal midshaft diameter (F6) showed the lowest correlation. For females the higher correlation was observed for the transverse midshaft diameter (F7) and the lowest for the upper sagittal diaphyseal diameter (F10). The RI of both sexes did not correlate with the BM (Tab. 4), but it correlated with the BMI (Tab. 5).

The BMI estimated with stature after Pearson varied between 25.2 and 27.0 for males and 23.2 and 25.3 for females (Tab. 3). The method of McHenry produced the lowest BMI for both males and females (25.2 resp. 23.3). The choice of stature estimation method produces variation on the BMI values, the higher the stature estimation the lower the BMI in both males and females. The mean difference between the highest and the lowest estimation methods was 1.3 BMI for males and 1.6 BMI for females (Tab. 3). Differences of BM and BMI between age groups are not significant with the exception of BM of males which is slightly significant (Tab. 7). Although in most cases not significant, there is a tendency of a slightly increased BM from young adults to mature adults, both males and females. Older adult males show a similar BMI compared to mature males, while older adult females exhibit a slightly lower BMI than mature ones.

Diachronic differences from the Early to the Late Middle Ages are slightly present. The differences of BM are not statistically significant, but the differences of BMI are significant for both males and females (Tab. 6). The increase of mean BMI from early to late medieval times is 1.1 for males and 1.2 for females.

Discussion

The four estimation methods for the body mass produced different results. McHenry´s BM is the lowest for both sexes, reflecting the reference series of small-bodied individuals used by him. Kurki and colleagues (2010) estimated the BM on a Holocene later Stone Age skeletal series from South Africa, a possible ancestral population of today´s Khoe San population. They suggested that McHenry´s (1992) formula produced the most reliable results compared to the bi-iliac breadth measurements. The Swiss medieval populations do not fall into the range of small bodied individuals considering at least the existing stature values (Lohrke and Cueni 2010, Siegmund 2010, Ulrich-Bochsler 2006), therefore a low BM by this method was expected. The method of Grine *et al.* (1995) produced the highest values for males and the second highest for females; again this was predictable, since the reference series used were large bodied modern Americans, while the Swiss medieval skeletal series were shorter and eventually lighter. The BM estimation after Ruff *et al.* (1991) produced values for males that lie in the middle of the other two methods while for the females produced the higher values. The results acquired from the Swiss data are in accordance to previous studies (Auerbach and Ruff 2004, Kurki *et al.* 2010). Based on the differences acquired and compared to previous studies it is evaluated that for the Swiss populations the mean of the three methods would give the most reliable BM estimation. A comparison of each method to the bi-iliac breadth would offer a more accurate proxy; however, in the absence of these measurements one is restricted to indirect comparisons. Therefore a new regression based on Swiss and/or Central European populations and datasets with additional variables such as the bi-iliac breadth should be considered.

Kurki *et al.* (2010) used the index of sexual dimorphism (ISD) to prove the plausibility of BM estimations. Their collection of 19 populations showed observed values of ISD raging from 0.069 to 0.211, with a mean of 0.142 and a standard deviation of 0.054. The BM estimations of the Swiss medieval populations (Tab. 2) are in concordance to that, with estimations after Ruff *et al.* (1991) coming closest to the expected ISD.

The estimation of the BMI on the skeletal material was not only influenced by the appropriate BM estimation method but also by the stature estimation method. The discussion on the most appropriate stature estimation method for the specific skeletal series has been made in previous studies (Siegmund 2010); nevertheless we underline once more that stature estimation is of great importance not only for intra- and interpopulation comparisons but for other applications such as the BMI estimation.

Strong correlations were observed between the external bone dimensions and the BM (Tab. 4). This underlines the association of BM and bone biomechanics illustrated by other studies as well (Ruff *et al.* 1991, Ruff *et al.* 1993). Tests on diaphyseal robusticity suggest that external metrical data can give valuable results regarding the strength of the bone (Stock and Shaw 2007). For male individuals the upper transverse diameter (F9) was the variable that correlated most strongly with the BM, while for females the transverse midshaft diameter (F7) exhibits the strongest correlation. This may be associated to the shape of the diaphysis; in some cases circumference provide better estimates of bone strength when periosteal contours are irregular or feature a significant interosseous crest, while midshaft diameters provide better results when diaphyses are elliptical or near circular (Stock and Shaw 2007). It should be mentioned, however, that post-cranial robusticity is strongly influenced by other factors such as climate, mobility and activity patterns (Stock and Pfeiffer 2001, Stock 2006). Since the populations used in the present study are geographically and chronologically very close to each other, we consider a similar influence of these factors on their post-cranial robusticity.

The Swiss medieval populations show no correlation between BM and the classical RI (Tab. 4), which may be attributed to the length standardization as seen in other studies (Holliday 2002). On the other hand BMI was slightly but significantly correlated with RI (Tab. 5). We interpret this more as an artefact due to the use of bone length in both variables.

The standard deviation on BM values in both sexes varies between 5.4 and 6.8 kg. Modern BM data from Swiss recruits show a standard deviation of 12–13 kg, however pre-industrial recruit data exhibit a lower standard deviation as reported by Staub and colleagues (2010). The mean BMI is 26.0 and 24.8 for males and females with a standard deviation of 2.3. In modern Switzerland 55% of the male and 65% of the female individuals show normal BMI values (18.5–24.9) and about 30% show overweight BMI values (≥30) (WHO, Global database on BMI). A direct comparison to modern BMI cut-off points can be misleading especially due to the high percentages of obese and overweight individuals. Staub and colleagues (2010) reported BMI values of Swiss recruit at the age of 19 years for the time periods 1875–1879 and 1933–1939; the mean BMI values are 20.6 ±1.9 and 21.4 ±2.0 for these periods. The values are extremely low in comparison to the values from the medieval skeletal material. One could expect more similarities between the pre-industrial BMI values rather to the modern data. Two factors could be responsible for the difference. The recruit BMI values were observed at the age of 19, at this point the skeletal development is not complete and – as reported by others studies – BMI is low compared to BMI values of adult and older individuals. There is a difference in the mechanical loading of the prehistoric population compared to modern humans. Activity patterns of past individuals varied substantially from average modern individuals (Weiss 2007), which may lead (1) to higher percentage of muscle versus fat in past populations, and (2) to an increased size of musculoskeletal stress markers. Both factors can substantially influence BM values, first because muscular individuals are heavier, and secondly because increased musculoskeletal stress markers have an effect on bone morphology and therefore can lead to increased BM estimations. Ruff (2000) explored the influence of activity patterns on BM by applying BM estimation methods to male Olympic athletes. He suggested that athletes may represent past populations better than "average" modern humans used in his BM estimations studies. In this study BM was underestimated in athletes that put a premium on strength and was overestimated in those that put a premium on endurance. He notes however that this overspecialization is rather unlikely to be present in early hominines or prehistoric populations and therefore he suggests that a combination of these physical qualities would be more plausible. It is probable that increased physical activity, as it is expected for the specific medieval populations, has lead to slightly increased bone dimensions and high muscle mass which on turn lead to slightly increased BMI. The "high" BMI values can also be attributed to a small stature; the BM values are relatively low (males: 71.7, females: 59.0) whereas the BMI values are rather high compared to modern data; this could be easily explained regarding that stature has significantly increased since the middle Ages (Koepke and Baten 2005, Maat 2005, Wurm 1982). This is systematically seen in the chronological differences between the Early, High and Late Middle Ages, where the BM decreases or remains the same whereas the BMI increases steadily. This phenomenon is related to a decrease of the stature in theses populations as described by other studies .

Age differences of BM and BMI values were not significant although there is a tendency of increased BM and BMI values with age especially in males. This is consistent with BM and BMI studies on modern populations (Janssen *et al.* 2011). The most weight is gained from the young adults to the mature adults whereas from the mature to the older adults the BM and the BMI either remain the same or slightly decrease. This is also a rather physiological phenomenon described in modern studies (Williamson 1993). However since the differences are not statistically significant further inferences would be rather speculative.

Conclusions

The present study tested BM and BMI estimation methods on a large dataset of Swiss medieval skeletal material. Previous observations on methodological aspects were similarly reported on the present study, suggesting that new reference data and new regression equations could optimize the results for the specific populations. Robusticity in terms of external femoral dimensions were highly correlated to BM, underlining the close relationship between biomechanics and bone adaptation. Acquired data show normal BM and normal to high BMI values suggesting either a higher muscle mass and increased activity patterns compared to modern individuals, or a smaller stature, or good living conditions. Although challenging BM and BMI reconstruction can offer valuable insights on the health and daily life of past populations.

Acknowledgments

The authors would like to thank Susi Ulrich-Bochsler and Viera Trancik Petitpierre for their permission to use unpublished data, and Wenke Hoyer for her valuable help acquiring some of the literature. Christina Papageorgopoulou thanks the Archaeological Service of Grisons for the financial support during the collection of the data and the Alexander v. Humboldt Foundation for financial support during the analysis of the data. Frank Siegmund thanks Tanya Uldin for her initial hint on this interesting scientific field.

References

Acsádi G, Nemeskéri J 1970. *History of human life span and mortality.* Hungarian Academic Society. Budapest.

Anthropologists WoE 1980. *Recommendations for age and sex diagnoses of skeletons.* Homo – Journal of Comparative Human Biology 9: 17–549.

Auerbach BM, Ruff CB 2004. *Human body mass estimation: A comparison of "morphometric" and "mechanical" methods.* American Journal of Physical Anthropology 125(4): 331–342.

Deurenberg P, Deurenberg-Yap M, Guricci S 2002. *Asians are different from Caucasians and from each other in their body mass index/body fat per cent relationship.* Obesity Reviews 3(3): 141–146.

Eknoyan G 2008. *Adolphe Quetelet (1796–1874) – the average man and indices of obesity.* Nephrology Dialysis Transplantation 23(1): 47–51.

Foucan L, Hanley J, Deloumeaux J, Suissa S 2002. *Body mass index (BMI) and waist circumference (WC) as screening tools for cardiovascular risk factors in Guadeloupean women.* Journal of Clinical Epidemiology 55(10): 990–996.

Franzosi MG 2006. *Should we continue to use BMI as a cardiovascular risk factor?* The Lancet 368 (9536): 624–625.

Gallagher D, Visser M, Sepúlveda D, Pierson RN, Harris T, Heymsfield SB 1996. *How useful is body mass index for comparison of body fatness across age, sex, and ethnic groups?* American Journal of Epidemiology 143(3): 228–239.

Grine FE, Jungers WL, Tobias PV, Pearson OM 1995. *Fossil Homo femur from Berg Aukas, northern Namibia.* American Journal of Physical Anthropology 97(2): 151–185.

Hartwig-Scherer S 1994. *Body weight prediction in fossil Homo.* Courier Forschungsinstitut Senckenberg 171: 267–279.

Hauser U 1938. *Anthropologische Untersuchung des alamanischen Gräberfeldes von Oerlingen Kt. ZH.* Diss. Univ. Zürich 1938. Basel.

Holliday TW 2002. *Body size and postcranial robusticity of European Upper Paleolithic hominins.* Journal of Human Evolution 43(4): 513–528.

Holliday TW, Franciscus RG 2009. *Body size and its consequences: Allometry and the lower limb length of Liang Bua 1 (Homo floresiensis).* Journal of Human Evolution 57(3): 223–228.

Janssen I, Shields M, Craig CL, Tremblay MS 2011. *Changes in the Obesity Phenotype within Canadian Children and Adults, 1981 to 2007–2009*. Obesity *(in print)*. doi:10.1038/oby.2011.122

Janosa M, Papageorgopoulou C 2012. *Die Sippengruft der Marmels in der Pfarrkirche St. Blasius zu Tinizong*. In: Jecklin-Tischhauser U, Frascoli L and Janosa M, editors. *Schweizer Beiträge zur Kulturgeschichte und Archäologie des Mittelalters 40*. Schweizerischer Burgenverein. Basel.

Kappelman J 1996. *The evolution of body mass and relative brain size in fossil hominids*. Journal of Human Evolution 30(3): 243–276.

Kaufmann B 1987. *Anthropologische Bearbeitung und Auswertung der menschlichen Skelettreste aus der Grabung Pratteln-Pfarreizentrum „Romana" 1976/77*. Jahresberichte aus Augst und Kaiseraugst 7: 177–242.

Kaufmann B 1989. *Güttingen TG „Grauer Stein": Bearbeitung der menschlichen Skelettreste aus den Grabungen 1927, 1966 und 1973*. Anthropologische Beiträge 2. Aesch.

Kaufmann B, Schoch M 1983. *Ried/Mühlehölzli: ein Gräberfeld mit frühmittelalterlichen und hallstattzeit-lichen Bestattungen*. 2 Bde. Universitätsverlag. Freiburg.

Koepke N, Baten J 2005. *The biological standard of living in Europe during the last two millennia*. European Review of Economic History 9 (01): 61–95.

Komlos J 2006. *The height increments and BMI values of elite Central European children and youth in the second half of the 19th century*. Annals of Human Biology 33(3): 309–318.

Komlos J, Brabec M 2010. *The trend of mean BMI values of US adults, birth cohorts 1882–1986 indicates that the obesity epidemic began earlier than hitherto thought*. American Journal of Human Biology 22(5): 631–638.

Komlos J, Breitfelder A, Sunder M 2009. *The transition to post-industrial BMI values among US children*. American Journal of Human Biology 21(2): 151–160.

Komlos J, Lauderdale BE 2007. *Spatial correlates of US heights and body mass indexes, 2002*. Journal of Biosocial Science 39 (01): 59–78.

Kurki HK, Ginter JK, Stock JT, Pfeiffer S 2010. *Body size estimation of small-bodied humans: Applicability of current methods*. American Journal of Physical Anthropology 141(2): 169–180.

Lakoski SG, Barlow CE, Farrell SW, Berry JD, Morrow Jr JR, Haskell WL 2011. *Impact of body mass index, physical activity, and other clinical factors on cardiorespiratory fitness (from the Cooper Center Longitudinal Study)*. The American Journal of Cardiology 108(1): 34–39.

Lohrke B, Cueni A 2010. *Anthropologische Untersuchungen zum frühmittelalterlichen Gräberfeld von Baar-Früebergstrasse*. In: Müller K, editor. *Gräber, Gaben, Gererationen: Der frühmittelalterliche Friedhof (7. Jahrhundert) von der Früebergstrasse in Baar (Kanton Zug)*. Basel, 60–122.

Maat GJR 2005. *Two millennia of male stature development and population health and wealth in the Low Countries*. International Journal of Osteoarchaeology 15(4): 276–290.

Martin R 1914. *Lehrbuch der Anthropologie in systematischer Darstellung: mit besonderer Berücksichtigung der anthropologischen Methoden: für Studierende, Ärzte und Forschungsreisende*. Fischer. Jena.

Martin R 1928. *Lehrbuch der Anthropologie in systematischer Darstellung: mit besonderer Berücksichtigung der anthropologischen Methoden für Studierende, Ärzte und Forschungsreisende*. 3 Bde. Fischer. Jena.

Martin R, and Saller K 1957. *Lehrbuch der Anthropologie in systematischer Darstellung: mit besonderer Berücksichtigung der anthropologischen Methoden*. 4 Bde. Fischer. Stuttgart.

McHenry HM 1992. *Body size and proportions in early hominids*. American Journal of Physical Anthropology 87(4): 407–431.

Papageorgopoulou C 2008. *The medieval population of Tomils: an archaeo-anthropological approach*. Phil. Diss. Univ. Basel.

Pearson K 1899. *Mathematical Contributions to the Theory of Evolution. V. On the Reconstruction of the Stature of Prehistoric Races*. Philosophical Transactions of the Royal Society of London Series A, Containing Papers of a Mathematical or Physical Character 192: 169–244.

Porter AMW 1999. *The prediction of physique from the skeleton*. International Journal of Osteoarchaeology 9(2): 102–115.

Prospective Studies C 2009. *Body-mass index and cause-specific mortality in 900.000 adults: collaborative analyses of 57 prospective studies*. The Lancet 373 (9669): 1083–1096.

Rafferty KL, Walker A, Ruff CB, Rose MD, Andrews PJ 1995. *Postcranial estimates of body weight in Proconsul, with a note on a distal tibia of P. major from Napak, Uganda*. American Journal of Physical Anthropology 97(4): 391–402.

Raxter MH, Auerbach BM, Ruff CB 2006. *Revision of the Fully technique for estimating statures*. American Journal of Physical Anthropology 130(3): 374–384.

Rössner S 2007. *Adolphe Quetelet (1796–1874)*. Obesity Reviews 8(2): 183–183.

Ruff C 1988. *Hindlimb articular surface allometry in hominoidea and Macaca, with comparisons to diaphyseal scaling*. Journal of Human Evolution 17(7): 687–714.

Ruff C 2010. *Body size and body shape in early hominins – implications of the Gona Pelvis*. Journal of Human Evolution 58(2): 166–178.

Ruff C, Niskanen M, Junno J-A, Jamison P 2005. *Body mass prediction from stature and bi-iliac breadth in two high latitude populations, with application to earlier higher latitude humans*. Journal of Human Evolution 48(4): 381–392.

Ruff CB, Holt BM, Sládek V, Berner M, Murphy JWA, zur Nedden D, Seidler H, Recheis W 2006. *Body size, body* *proportions, and mobility in the Tyrolean "Iceman"*. Journal of Human Evolution 51(1): 91–101.

Ruff CB, Scott WW, Liu AYC 1991. *Articular and diaphyseal remodeling of the proximal femur with changes in body mass in adults*. American Journal of Physical Anthropology 86(3): 397–413.

Ruff CB, Trinkaus E, Holliday TW 1997. *Body mass and encephalization in Pleistocene Homo.* Nature 387 (6629): 173–176.

Ruff CB, Trinkaus E, Walker A, Larsen CS 1993. *Postcranial Robusticity in Homo. 1: Temporal trends and mechanical interpretation*. American Journal of Physical Anthropology 91(1): 21–53.

Rühli F, Henneberg M, Woitek U 2008. *Variability of height, weight, and body mass index in a Swiss armed forces 2005 census*. American Journal of Physical Anthropology 137(4): 457–468.

Rush EC, Goedecke JH, Jennings C, Micklesfield L, Dugas L, Lambert EV, Plank LD 2007. *BMI, fat and muscle differences in urban women of five ethnicities from two countries*. International Journal of Obesity 31(8): 1232–1239.

Siegmund F 2010. *Die Körpergrösse der Menschen in der Ur- und Frühgeschichte Mitteleuropas und ein Vergleich ihrer anthropologischen Schätzmethoden.* Books on Demand. Norderstedt.

Sluyter JD, Schaaf D, Scragg RKR, Plank LD 2011. *Body mass index and percent body fat in a New Zealand multi-ethnic adolescent population.* International Journal of Pediatric Obesity 6(1): 36–44.

Staub K, Rühli FJ, Woitek U, Pfister C 2010. *BMI distribution: social stratification in Swiss conscripts from 1875 to present.* European Journal of Clinical Nutrition 64(4): 335–340.

Stock J, Pfeiffer S 2001. *Linking structural variability in long bone diaphyses to habitual behaviors: Foragers from the southern African Later Stone Age and the Andaman Islands*. American Journal of Physical Anthropology 115(4): 337–348.

Stock JT 2006. *Hunter-gatherer postcranial robusticity relative to patterns of mobility, climatic adaptation, and selection for tissue economy.* American Journal of Physical Anthropology 131(2): 194–204.

Stock JT, Shaw CN 2007. *Which measures of diaphyseal robusticity are robust? A comparison of external methods of quantifying the strength of long bone diaphyses to cross-sectional geometric properties*. American Journal of Physical Anthropology 134(3): 412–423.

Trancik-Petitpierre V 1991. *Die anthropologische Auswertung der frühmittelalterlichen Skelette aus der Kirche St. Peter und Paul zu Oberwil.* Archäologie und Museum. Amt für Museen und Archäologie. Liestal.

Ulrich-Bochsler S 2009. *Anthropologische Auswertung der Gräber.* In: Eggenberger P, Bacher R, Frey J, Frey-Kupper S, Heigold-Stadelmann A, and Ulrich-Bochsler S, editors. *Seeberg, Pfarrkirche: die Ergebnisse der Bauforschungen von 1999/2000.* Archäologischer Dienst des Kantons Bern. Bern, 217–248.

Ulrich-Bochsler S 2006. *Anthropologische Rekonstruktion einer frühmittelalterlichen Bevölkerung aus dem Berner Seeland.* In: Kissling C, and Ulrich-Bochsler S, editors. *Kallnach-Bergweg: Das frühmittelalterliche Gräberfeld und das spätrömische Gebäude*. Rub Media. Bern, 113–176.

Ulrich-Bochsler S 1988. *Die anthropologischen Forschungen.* In: Eggenberger P, Rast Cotting M, and Ulrich-Bochsler S, editors. *Rohrbach: Reformierte Pfarrkirche.* Haupt. Bern, 103–111.

Ulrich-Bochsler S, Meyer L 1994. *Die anthropologischen Forschungen.* In: Eggenberger P, and Ulrich-Bochsler S, editors. *Steffisburg: Reformierte Stadtkirche.* Haupt. Bern, 101–159.

Ulrich-Bochsler S, Meyer L 1992. *Die anthropologischen Forschungen.* In: Eggenberger P, Bossert M, and Ulrich-Bochsler S, editors. *Walkringen: Reformierte Pfarrkirche.* Staatlicher Lehrmittelverlag. Bern.

Vančata V, Charvátová M 2001. *Post-palaeolithic Homo Sapiens evolution in central Europa: Changes in body size and proportions in the neolithic and early bronze age.* Anthropologie – International Journal of the Science of Man 39: 133–152.

Vercellotti G, Agnew AM, Justus HM, Sciulli PW 2009. *Stature estimation in an early medieval (XI–XII c.) Polish population: Testing the accuracy of regression equations in a bioarcheological sample*. American Journal of Physical Anthropology 140(1): 135–142.

Weiss E 2007. *Muscle markers revisited: Activity pattern reconstruction with controls in a central California Amerind population*. American Journal of Physical Anthropology 133(3): 931–940.

Wheatley BP 2005. *An evaluation of sex and body weight determination from the proximal femur using DXA technology and its potential for forensic anthropology.* Forensic Science International 147(2–3): 141–145.

WHO. *Global database on BMI.* <http://apps.who.int/bmi/index.jsp> (visited 18. 5. 2011).

Williamson DF 1993. *Descriptive epidemiology of body weight and weight change in U.S. adults.* Annals of Internal Medicine 119(2): 646–649.

Wurm H 1982. *Über die Schwankungen der durchschnittlichen Körperhöhe im Verlauf der deutschen Geschichte und die Einflüsse des Eiweißanteiles der Kost.* Homo – Journal of Comparative Human Biology 33: 21–42.

Address:

Frank Siegmund
Dittingerstrasse 33
4053 Basel
Switzerland