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Secular trends in anthropometric characteristics and their associations with external skeletal robustness among Slovenian young adults' population

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Abstract

Objectives To determine secular trends in anthropometric indices (fat-mass, fat-free mass, external skeletal robustness) in young adults and examine possible relationships between them.

Methods Anthropometric data (body height, body mass; skinfold thickness (SFT) – triceps, abdominal, thigh; circumferences (C) – waist, upper arm, thigh; width – elbow, knee) of young adults aged 20–25 years (N=5303; males 1985, females 3318) were used from the Slovenian (data)Base of Anthropometric Measurements from 1960 to 2023. Multiple linear regressions were performed.

Results The most significant positive secular trends ($p<0.0001$) were observed in males for abdominal SFT ($B=0.151$, $R^2=0.169$) and thigh SFT ($B=0.131$, $R^2=0.142$). In females, similar trend was observed in waist C ($B=0.111$; $R^2=0.107$). The most significant negative secular trend ($p<0.001$) was observed in muscle area of lower limbs in both sexes (males: $B=-0.427$, $R^2=0.000$; females: $B=-0.875$, $R^2=0.300$). Based on multiple linear regression analysis, body height and overall body mass were the most important factors influencing the observed decline in external skeletal robustness, with the latter being assessed with frame index according to elbow and knee width.

Conclusion Over the last 60 years, a positive secular trend was observed in body height and body fat, while a negative trend was noted in muscle mass. Increases in body height and overall body mass had the most significant impact on the observed decrease in assessed external skeletal robustness over time.

Take home message for students Over the past six decades, Slovenian young adults have grown taller, gained fat, lost muscle mass, and their external skeletal robustness diminished.

Abbreviations

ANOVA one-way analysis of variance
B unstandardized beta
BAM (data)Base of Anthropometric Measurements
BFP percentage of body fat
BMI body mass index
C circumferences
CI confidence interval
FI frame index
FI.elbow frame index from elbow width
FI.knee frame index from knee width
ISAK The International Society for the Advancement of Kinanthropometry
N number of subjects
OW overweight
P value of statistical significance
R^2 adj. and adjusted R-squared R^2 adj.
SFT skinfold thickness
TMA thigh muscle area
UMA upper arm muscle area

Introduction

The term *secular trend in human growth* refers to a long-term, noticeable, and consistent change in body characteristics of a population over an extended period of time (i.e., several decades or even centuries) (Bogin 2021a). It illustrates the complex interplay of genes, physiology, and environment in determining the size and shape of individuals from one generation to the next (Cole 2003). The direction and rate of secular trends of population groups generally correspond to the standard of living (assessed with, for example, gross domestic product per capita, access to health care, and nutrition) within a country (Bogin 2021a), which was traditionally used as an indicator of population's public health.

One of the best documented positive secular trends is the increase in average height and body mass that began in the mid-19th century (Cole 2003; Fudvoye and Parent 2017). Body height is influenced by several factors that can alter an individual's genetic growth potential (Rogol et al. 2000). In addition to genetic predispositions, body height in adulthood is associated with a higher standard of living and the socioeconomic structure of the country (Chen and Ji 2013; Hermanussen and Scheffler 2016; Łopuszańska-Dawid and Szklarska 2020; Bogin 2021a). Furthermore, some authors suggested that human height is the result of complex regulation of human growth in response to social status in the community (Bogin et al. 2018; Bogin 2021b; Scheffler and Hermanussen 2022).

It has been noted that average body height has already reached a plateau in several countries, for example in Northern European countries (e.g. Netherland, Finland, Denmark, and Sweden), the UK, India, and Bangladesh (NCD Risk Factor Collaboration 2016; Fudvoye and Parent 2017). However, over the same period, a shift toward an increase in body mass over height can be observed. Due to environmental and behavioural changes (Caballero 2007; Temple 2023), the global epidemic of overweight and obesity began in the 1980s in developed countries (Ng et al. 2014; Cole 2003; Garrido-Miguel et al. 2019; Afshin et al. 2017).

The main mechanism for the development of obesity is energy imbalance, in which excessive caloric intake exceeds the energy expenditure (e.g., through physical activity). This imbalance leads to the accumulation of body fat and often to a decrease in lean body mass which can affect the robustness of the skeleton (Rietsch et al. 2013a; Lizana and Hormazabal-Peralta 2020). External skeletal robustness is a term that refers to the skeletal strength as reflected by its size and shape (Stock and Shaw 2007) and it is described with body frame size. Body frame size is frequently assessed with the diameter of certain bone structures, with elbow width according to the height being the most often used proxy for the body frame size (Frisancho 1990; La Guzman-de Garza et al. 2022). Body frame size can be influenced by body composition (fat mass, fat-free mass) and total body mass (Chumlea et al. 2002). Indeed, both muscle and fat mass, which exert dynamic loads and additional gravitational pressure on bone, affect the bone structure and strength (Jeddi et al. 2015; Behringer et al. 2014).

Body frame size has been extensively studied in children and adolescents (La Guzman-de Garza et al. 2022). Several studies found a positive association between the percentage of body fat (BFP) and the external skeletal robustness measured with body frame size (La Guzmán-de Garza et al. 2017; Leonard et al. 2004; Musálek et al. 2018; Rietsch et al. 2013a; Martinez et al. 1995; Vispute et al. 2023; Lizana and Hormazabal-Peralta 2020). In contrast, some studies in children and adolescents aged 6 to 12 years showed opposite results, although this was not true for all examined ages of children (Scheffler 2010). Furthermore, a study conducted by Kryst et al. (Kryst et al. 2021) demonstrated that normal-weight individuals had greater bone and muscle mass, which also resulted in better scores on most fitness tests (e.g., relative dynamometric strength) compared to their overweight/obese peers (Kryst et al. 2021). The amount of fat mass also appears to have a negative impact on the skeletal robustness in normal-weight obese individuals (thus in those with normal BMI but excess total body fat and low lean body mass). Namely, the results of the Musálek et al. (Musálek et al. 2018) study showed poorer skeletal robustness of the lower extremities in normal-weight obese children. Furthermore, Deng et al. (Deng et al. 2021) proposed that higher lean body mass is associated with higher bone mineral density, while higher BFP seems to have a negative effect on bone mineral density in children and adolescents.

There are a few studies that explore skeletal robustness and its associations with body fatness in the adult population. The study of Martinez et al. (Martinez et al. 1995) demonstrated that body frame size is positively associated with the amount of subcutaneous fat (independent of age and sex) in children, adolescents, as well as in young adults, which is in direct contrast with the observations of Scheffler (Scheffler 2010). However, the study by Glauber et al. (Glauber et al. 1995) demonstrated that the most important factor associated with higher bone mineral density was body mass, especially for weight-bearing bones (such as the hip bone and the vertebrae), as compared to height, hip-to-waist ratio, elbow width, and body fat percentage.

Since the second half of the 20th century, a positive trend in overweight/obesity (fat mass) (Olds 2009; Finucane et al. 2011; Guimarey et al. 2014; González-Álvarez et al. 2020; Robič Pikel 2022) and a negative trend in fat-free body mass (Sun et al. 2012; Guimarey et al. 2014) have been observed. To the best of our knowledge, no studies have yet been conducted that have investigated the secular trend in the external skeletal robustness in adults. However, the external skeletal robustness in children decreased over the same period (Scheffler 2010; Scheffler and Hermanussen 2014; Rietsch et al. 2013b; Navazo et al. 2020).

Changes in body height (Cole 2003; Fudvoye and Parent 2017) and overweight/obesity (Afshin et al. 2017; Garrido-Miguel et al. 2019) have been widely studied worldwide. However, studies on changes in other body characteristics and body proportions, as well as on the effects of excessive body fat accumulation on growth, are limited and results are inconsistent. Therefore, using a (data)Base of Anthropometric Measurements (BAM) of the Slovenian student population (Golja and Robič Pikel 2021), we aimed to reveal secular trends of anthropometric indices (fat mass, fat-free mass, skeletal robustness) of young adults and examine possible relationship between them. We hypothesized that body size of young Slovenian adults (students) changed over last 63 years as follows: (1) average body height and body fat mass (as assessed with skinfold thickness and waist circumference) increased; (2) skeletal robustness (as assessed with frame index) decreased and (3) skeletal robustness is negatively associated with body fatness.

Sample and methods

Study sample

The data for the present study were obtained from an extensive anthropometric data collection, that was established over years from measurements performed on Slovenian males and females of the (mostly) student population – (data)Base of Anthropometric Measurements (BAM) (Golja and Robič Pikel 2021; Robič Pikel 2022). Briefly, the Department of Biology of the Biotechnical Faculty of the University of Ljubljana, Slovenia, has been performing systematic anthropometric measurements on young adults (mostly students) annually since the 1930s. Most of the measurements were performed on subjects who enrolled in one of the study programmes of the University of Ljubljana, mainly those of the Biotechnical Faculty or Faculty of Education. In the decade 1960–69, data were also obtained as a part of preventive health care activities for students at the University of Ljubljana. In addition, BAM also includes data that have been collected as a part of different master's and doctoral degree theses. For this purpose, colleagues/acquaintances of the students are sometimes invited to participate – these subjects are in the same age group than the students, but do not necessarily study themselves. Subjects have provided written informed consent and the use of all collected anonymized anthropometric data was approved by the National Ethics Committee of the Republic of Slovenia (KME 104/12/10).

To achieve the aims of the present study, anthropometric data of young adults (mainly students) were collected from BAM for the subjects measured between 1960 and 2023. The recruited subjects were enrolled in one of the study programmes of the University of Ljubljana and came from different parts of the Republic of Slovenia. The sample was thus not randomised. Since slightly different measurements were performed in different time periods, only correctly performed measurements were selected for the present analysis.

Measurements

Anthropometric characteristics were measured in accordance with anthropometric standards (Lohman 1988). Body height was measured with a stadiometer to the nearest 0.1cm. During the measurement, subjects stood barefoot, with their back straight, hands relaxed next to their body, feet and knees together, heels touching the stadiometer, and head held in the Frankfurt horizontal plane. After year 2020, we started to measure body height according to the International Society for the Advancement of Kinanthropometry (ISAK) standard, which is, in comparison to the standards set by Lohman et al. (Lohman 1988), a stretched body height. Body mass was measured with a certified medical scale to the nearest 0.1kg. During the measurement, subjects stood still over the center of the scale, with the body mass evenly distributed over both feet (Lohman 1988).

Skinfold thickness (SFT) (triceps, thigh, and abdominal) was measured on the right side of the body with skinfold caliper to the nearest 0.1mm, which was a Slim Guide caliper (HaB Essentials) before 2010, and a Harpenden caliper (HSB-BI, England) after 2010. The measurement of each skinfold was performed three times and the median of the measurements was taken as representative. The triceps SFT was measured vertically over the triceps muscle midway between the acromial process of the scapula and olecranon process of the ulna (or at the anthropometric landmark radiale after the year 2020 according to ISAK). The thigh SFT was measured vertically in the front of thigh at mid-point between the anthropometric landmark patellare and the mid-point of inguinal ligament. The abdominal SFT was measured vertically, 5cm to the right from the umbilicus.

Circumferences (C) were measured with non-elastic tape to the nearest 0.1cm. Waist C was measured at a level midway between the lower rib margin and iliac crest all around the body in horizontal position, relaxed mid-upper arm C at the same level as triceps SFT, and thigh C at the same level as thigh SFT.

Elbow and knee width were measured with the small sliding caliper to the nearest 0.1cm between the lateral and medial epicondyle of the humerus and femur, respectively.

It should be noted that the measuring devices have changed over the decades but were standard equipment at the time.

Calculations

All the equations used are presented in Table 1.

Statistical analysis

All data were analysed using IBM SPSS Statistics 22 (IBM Corp. 2022). The level of statistical significance was set to 0.05. Because the variables were normally distributed (as assessed with the normal Q-Q plot, skewness, kurtosis, and normality test), all parametric data (body height, body mass, BMI, triceps SFT, and thigh SFT, waist C, elbow and knee width, and frame index according to elbow and knee) were presented as average (standard deviation), and statistical analysis was performed using the appropriate parametric tests. To test the differences in average value of the selected variables between the decades, one-way analysis of variance (ANOVA) was performed. Because of the inequality of variance between the decades, the robust Welch test was used.

To examine the secular trends of variables in question, a simple linear regression was performed between the year of measurement as an independent variable (outcome) and each selected variable as the dependent (predicted) variable. Results are presented as unstandardized beta (B) and adjusted R-squared (R^2 adj.).

Multiple linear regression (stepwise method) was performed to examine whether external skeletal robustness assessed with the frame index according to elbow width (FI.elbow) and knee width (FI.knee), was associated with the predicted variables (height, body mass, triceps SFT, upper arm muscle area (UMA), thigh SFT, and thigh muscle area (TMA)). When FI.elbow was used as the dependent variable, body height, body mass, triceps SFT, and UMA were included in the model. If FI.knee was used as the dependent variable, body height, body mass, thigh SFT, and TMA were included in the model. We excluded all cases with standardised residuals greater than +3 or smaller than -3.

Results

Our final sample included 5,303 young adults (males N=1,985, females N=3,318) with average age of 21.5 years (range 20- to 25-years-olds).

In Table 2, the sex structure of the sample during the six decades is presented. Table 3 (for males) and Table 4 (for females) present anthropometric characteristics of our sample in each decade. ANOVA revealed statistical significance ($p<0.001$) between decades for each studied variable (p-values are not presented in the table). Over the examined decades, average body height increased, with the most significant change observed in 1980–89 and then 2000–09 compared to the other decades in both sexes. Average body mass also increased over the decades, particularly after the decade 2000–09.

Anthropometric characteristics for assessing overweight/obesity generally increased over time. The most significant and consistent increase was observed for waist C from the decade 1960–69 to the decade 2010–19 in both sexes. Average BMI significantly increased from the decade 1960–69 to the decade 2020–23 in males, but not in females. However, the prevalence of overweight/obesity according to BMI increased over the same period in both sexes, from 12.5% to 20.3% in males and from 11.4% to 18.4% in females. The observed prevalence of overweight/obesity according to BMI was not statistically significant between males and females ($p>0.05$).

Muscle mass assessed with upper arm muscle area (UMA) significantly increased in the decade 2010–19 and 2020–23, while thigh muscle area (TMA) decreased in the same period in both sexes.

Anthropometric characteristics for assessing external skeletal robustness (assessed with frame index) according to elbow width (FI.elbow) decreased significantly over time, especially after the 2010–19 decade in males, and in the 2020–23 decade in females. In males, elbow width decreased significantly after 2010–19, whereas for FI.elbow, a decrease was already observed after 2000–09. In females, both measures were the lowest in 2010–19. No such pattern was seen in FI.knee in males, while in females a decrease in FI.knee was more pronounced from the decade 1960–69 to the decade 2010–19, with an observed increase in the decade 2020–23.

Additional simple linear regression (Table 5 for males and Table 6 for females) confirmed the above presented results. Positive secular trends were observed for body height (1.0cm per decade in males and 0.7cm per decade in females) and body mass (1.2kg per decade in males and 0.6kg per decade in females). Among measures assessing overweight/obesity, the greatest positive change over time was observed

Table 1 Equations used for the assessment of overweight/obesity, lean body mass, and external skeletal robustness.

Calculated variable	Abb	Equation	Unit	Reference
Body mass index	BMI	body mass/body height2	[kg/m2]	(Quetelet 1869 (reprint 2018))
Upper arm muscle area	UMA	(C upper arm2/4*π)-(C upper arm*triceps SFT/2)	[cm2]	(Rolland-Cachera et al. 1997)
Thigh muscle area	TMA	(C thigh2/4*π)-(C thigh*thigh SFT/2)	[cm2]	(Musálek et al. 2018)
Frame index from elbow width	FI.elbow	(elbow width [mm]*100)/body height [cm]	[%]	(Frisancho 1990)
Frame index from knee width	FI.knee	(knee width [mm]*100)/body height [cm]	[%]	(Musálek et al. 2018)

Abb – abbreviation, C – circumference, SFT – skinfold thickness in abdominal SFT (1.5mm per decade) in males, and in waist C (1.1cm per decade) in females, while the smallest change was observed in BMI (0.1kg/m2 per decade for males, -0.03kg/m2 per decade for females). Significant negative secular trend was observed in muscle mass, especially in TMA (-4.3cm2 in males and -8.8cm2 in females). Among measures assessing skeletal robustness, a negative secular trend was observed for both FI.elbow and FI.knee (-0.4 percentage points per decade for both measures in males; -0.4 percentage points per decade for FI.elbow and 0.8 percentage points per decade for FI.knee in females).

Selected measures for the assessment overweight/obesity (triceps SFT, abdominal SFT), muscle mass (UMA, TMA), and external skeletal robustness (FI.elbow, FI.knee) are presented in Figure 1 for males and Figure 2 for females.

The results of multivariate linear regression (enter method) are presented in Table 7 for males and females, separately. In the multivariate model, body height had the highest negative correlation with both FI.elbow and FI.knee in both sexes. In contrast, body mass had the highest positive correlation on both indices in both sexes. These two variables together explained most of the variance in the regression model (as seen from the results of a stepwise method).

Discussion

According to the results of the present study, we were able to confirm our first and second hypotheses, as well as the third in part. Regarding the first hypothesis, the average body height and body fat (as assessed with skinfold thickness and waist circumference), especially in the abdominal area in males, have increased significantly over the last 63 years. With respect to the second, external skeletal robustness (as assessed with frame index) has decreased in the same period. Lastly, concerning the third hypotheses, external skeletal robustness is negatively associated with body fat, but the most important factor contributing to the observed decrease in external skeletal robustness over time was the positive secular trend in body height and total body mass, regardless of source.

Secular trend in body height

Results of the present study revealed significant positive secular trends in average body height in the Slovenian young adult population from 1960 to 2023 which confirms the previous findings in the Slovenian young adult population (Robič Pikel 2022; Robič Pikel et al. 2023), as well as the children's and adolescents' population

Table 2 Sex structure of the Slovenian sample.

	All subject	Males		Females	
Decade	**N**	**N**	**%**	**N**	**%**
1960-69	1863	979	53	884	47
1980-89	829	506	61	323	39
1990-99	622	144	23	478	77
2000-09	722	102	14	620	86
2010-19	928	169	18	759	82
2020-23	333	81	24	252	76

N – number of subjects

(Đurić et al. 2021). The observed significant increase in body height is in line with the situation in other developed countries worldwide (Fudvoye and Parent 2017; NCD

Table 3 Anthropometric characteristics of the sample by decades for Slovenian males. Results presented as average (standard deviation.

Time period [years]		1960-69	1980-89	1990-99	2000-09	2010-19	2020-23
Age	[years]	22.0 (1.6)	20.4 (0.6)	21.1 (0.8)	21.5 (1.1)	21.4 (1.4)	21.7 (1.4)
Body height	N	979	506	144	102	169	81
	[cm]	175.8 (6.2)	179.1 (6.1)	179.4 (6.8)	180.4 (6.5)	180.5 (6.4)	181.1 (6.6)
Body mass	N	981	506	144	102	165	74
	[kg]	70.1 (8.1)	72.8 (8.2)	72.3 (8.9)	75.3 (12.6)	77.3 (13.0)	75.6 (9.9)
Anthropometric characteristics for assessing overweight/obesity							
BMI	N	979	506	144	102	165	74
	[kg/m^2]	22.7 (2.1)	22.7 (2.2)	22.4 (2.4)	23.1 (3.2)	23.7 (3.5)	23.1 (2.6)
OW/obese	N	122	59	23	24	41	15
according to BMI	[%]	12.5	11.7	16.0	23.5	25.0	20.3
Waist C	N	966	268	88	101	168	81
	[cm]	76.3 (5.5)	78.7 (6.2)	79.8 (6.7)	80.5 (8.6)	82.5 (8.6)	80.2 (7.5)
Abdominal SFT	N	942	268	62	/	89	50
	[mm]	8.5 (5.2)	13.9 (7.4)	13.3 (6.9)		16.1 (7.7)	15.3 (7.2)
Triceps SFT	N	976	411	144	100	167	67
	[mm]	7.0 (3.5)	9.7 (3.4)	9.9 (4.2)	11.7 (4.9)	10.4 (4.9)	10.1 (4.3)
Thigh SFT	N	880	268	63	/	89	49
	[mm]	10.3 (5.2)	15.6 (6.3)	13.6 (6.0)		17.2 (8.4)	15.9 (7.2)
Anthropometric characteristics for assessing lean body mass							
Upper arm C	N	980	411	144	101 29.4 (3.1)	164	80
	[cm]	28.8 (2.5)	28.6 (2.3)	29.4 (2.8)	29.4 (3.1)	30.4 (3.3)	30.1 (3.0)
Thigh C	N	958	268	62	/	70	62
	[cm]	54.5 (4.3)	56.0 (4.2)	56.0 (3.9)		53.1 (5.6)	51.4 (5.1)
UMA	N	974	410	144	100	163	66
	[cm^2]	56.4 (10.3)	51.4 (7.9)	54.6 (10.8)	52.0 (9.6)	58.2 (13.5)	58.1 (11.8)
TMA	N	879	267	62	/	68	48
	[cm^2]	209.5 (30.1)	206.1 (26.2)	212.3 (27.4)		183.5 (42.6)	171.7 (38.6)
Anthropometric characteristics for assessing external skeletal robustness							
Width elbow	N	844	269	131	87	122	65
	[cm]	7.1 (0.5)	7.1 (0.3)	7.1 (0.4)	7.0 (0.6)	6.9 (0.4)	6.9 (0.4)
Width knee	N	843	269	129	87	118	63
	[cm]	9.9 (0.5)	9.8 (0.4)	9.8 (0.5)	9.8 (0.6)	9.7 (0.7)	10.0 (1.4)
FI.elbow	N	841	269	131	87	122	65
	[%]	40.5 (2.6)	39.6 (1.9)	39.8 (1.9)	38.9 (2.9)	38.0 (2.1)	38.1 (2.0)
FI.knee	N	840	269	129	87	118	63
	[%]	56.3 (2.8)	54.6 (2.5)	54.6 (2.5)	54.3 (3.4)	54.0 (3.7)	55.7 (7.4)

N – number of subjects, BMI – body mass index, OW – overweight, C – circumference, FI – frame index, SFT – skinfold thickness, TMA – thigh muscle area, UMA – upper arm muscle area

Risk Factor Collaboration 2016). Although a comprehensive comparison of changes in body height between our and other studies was not the scope of the present study, we

Table 4 Anthropometric characteristics of the sample by decades for Slovenian females. Results presented as average (standard deviation).

Time period [years]		1960-69	1980-89	1990-99	2000-09	2010-19	2020-23
Age	[years]	21.9 (1.5)	20.0 (0.5)	21.6 (1.2)	21.7 (1.2)	21.5 (1.5)	21.6 (1.5)
Body height	N	884	323	478	620	759	252
	[cm]	163.5 (5.9)	166.2 (6.2)	166.6 (5.9)	166.9 (6.3)	167.1 (5.8)	168.0 (6.5)
Body mass	N	884	322	478	619	738	237
	[kg]	59.1 (7.3)	59.1 (7.4)	59.5 (9.1)	61.8 (10.6)	61.8 (9.8)	63.4 (12.5)
Anthropometric characteristics for assessing overweight/obesity							
BMI	N	884	322	478	619	738	237
	[kg/m^2]	22.1 (2.3)	21.4 (2.3)	21.4 (3.0)	22.2 (3.6)	22.1 (3.2)	22.5 (4.5)
OW/obese	N	101	22	41	98	105	43
according to BMI	[%]	11.4	6.9	8.6	15.9	14.3	18.4
Waist C	N	862	157	156	620	749	241
	[cm]	67.4 (5.4)	68.7 (5.5)	69.3 (6.3)	72.7 (8.3)	73.5 (7.7)	71.6 (8.8)
Abdominal SFT	N	771	155	41	/	307	122
	[mm]	17.5 (8.4)	14.9 (5.8)	13.1 (6.1)		18.9 (6.7)	15.2 (7.4)
Triceps SFT	N	874	284	478	620	750	199
	[mm]	13.4 (4.7)	14.6 (4.6)	15.1 (5.5)	17.7 (6.0)	16.4 (5.8)	16.5 (6.9)
Thigh SFT	N	767	154	41	/	306	123
	[mm]	24.9. (8.9)	26.7 (7.0)	23.5 (8.5)		27.0 (8.9)	25.8 (11.4)
Anthropometric characteristics for assessing lean body mass							
Upper arm C	N	881	280	478	620	747	244
	[cm]	27.5 (2.5)	(26.1)	26.2 (2.9)	27.1 (3.2)	27.1 (3.0)	27.2 (3.9)
Thigh C	N	813	157	41	/	212	154
	[cm]	56.5 (4.2)	55.6 (4.0)	56.2 (4.1)		50.6 (5.1)	49.8 (6.6)
UMA	N	871	278	478	620	742	197
	[cm2]	42.1 (8.6)	35.2 (5.8)	35.1 (7.4)	34.4 (7.2)	36.6 (9.4)	36.8 (10.2)
TMA	N	767	153	41	/	180	122
	[cm2]	184.8 (31.1)	172.6 (26.1)	185.2 (25.2)		134.6 (29.7)	135.4 (55.7)
Anthropometric characteristics for assessing external skeletal robustness							
Width elbow	N	741	163	299	359	539	175
	[cm]	6.2 (0.3)	6.1 (0.4)	6.1 (0.4)	6.1 (0.5)	6.0 (0.5)	6.1 (0.6)
Width knee	N	740	163	299	359	493	175
	[cm]	9.3 (0.5)	8.9 (0.5)	8.8 (0.7)	8.8 (0.7)	8.8 (0.8)	9.0 (0.7)
FI.elbow	N	740	163	299	359	539	175
	[%]	37.9 (1.9)	37.0 (2.2)	36.8 (2.4)	36.6 (3.0)	35.6 (2.8)	36.6 (4.0)
FI.knee	N	739	163	299	359	493	175
	[%]	56.9 (2.9)	53.5 (2.9)	52.8 (3.7)	52.4 (4.3)	52.7 (4.9)	53.5 (4.7)

N – number of subjects, BMI – body mass index, C – circumference, FI.elbow – Frame index according to elbow width, FI.knee – Frame index according to knee width, SFT – skinfold thickness, TMA – thigh muscle area, UMA – upper arm muscle area nevertheless made some comparisons with other similar studies. For example, the observed increase in body height for 1.0cm per decade in males is comparable to approximately 0.9cm increase in body height per decade in the study of Kirchengast et al. (Kirchengast et al. 2023) in Austrian male conscripts between 1951 and 2002, and smaller than 1.4cm increase in body height per decade in Polish male students between 1959 to 2011 (Kalka et al. 2019), as well as with 1.7cm increase in body height per decade in Polish male conscripts between 1965 and 2010 (Kołodziej et al. 2015). For females, the observed increase in body height for 0.7cm per decade in our study was lower than the 1.34cm increase in body height per decade reported by Łopuszańska-Dawid & Szklarska (Łopuszańska-Dawid and Szklarska 2020) in Polish adults between 1931 and 2020. Despite a continuous increase in average body height in our study, the rate of this increase varied over time. In our study, the most significant increase in average body height was observed in the decades 1980–89, 2000–10, and 2020–23. Such a rapid change in height over decades was also observed in other studies mentioned above (Kołodziej et al. 2015; Kalka et al. 2019; Kirchengast et al. 2023; Łopuszańska-Dawid and Szklarska 2020; Negasheva et al. 2024). Some studies showed that the average body height stabilised by 2000 in some populations, i.e. in Polish women (Łopuszańska-Dawid and Szklarska 2020) and in the Russian population (Negasheva et al. 2024) which was also observed in our study. It should

Table 5 Secular trends of different anthropometric characteristics, presented as results of a simple linear regression, with the year of measurement as an independent variable and corresponding dependent variables, for males.

			Males			
Independent variable		N	B	95% CI	p	R^2 adj.
Body height	[cm]	1981	0.099	0.084, 0.113	<0.001	0.085
Body mass	[kg]	1972	0.120	0.099, 0.140	<0.001	0.062
Anthropometric characteristics for assessing overweight/obesity						
BMI	[kg/m2]	1970	0.012	0.006, 0.017	<0.001	0.009
Waist C	[cm]	1672	0.099	0.085, 0.114	<0.001	0.096
Abdominal SFT	[mm]	1410	0.151	0.134, 0.169	<0.001	0.169
Triceps SFT	[mm]	1865	0.075	0.067, 0.084	<0.001	0.130
Thigh SFT	[mm]	1348	0.131	0.113, 0.148	<0.001	0.142
Anthropometric characteristics for assessing lean body mass						
Upper arm C	[cm]	1880	0.024	0.018, 0.030	<0.001	0.033
Thigh C	[cm]	1420v	-0.015	-0.028, -0.002	0.023	0.003
UMA	[cm2]	1857	-0.004	-0.028, 0.021	0.773	0.000
TMA	[cm2]	1322	-0.427	-0.518, -0.336	<0.001	0.060
Anthropometric characteristics for assessing external skeletal robustness						
Width elbow	[cm]	1518	-0.004	-0.005, -0.003	<0.001	0.028
Width knee	[cm]	1509	-0.003	-0.004, -0.002	<0.001	0.011
FI.elbow	[%]	1515	-0.041	-0.046, -0.035	<0.001	0.112
FI.knee	[%]	1506	-0.043	-0.050, -0.036	<0.001	0.091

N – number of subjects, BMI – body mass index, C – circumference, SFT – skinfold thickness, FI.elbow – Frame index according to elbow width, FI.knee – Frame index according to knee width, TMA – thigh muscle area, UMA – upper arm muscle area, R^2 adj. – adjusted R squared, B – unstandardized beta, CI – confidence interval, p – value of statistical significance be noted that the significant increase in average body height in the decade 2020–23 observed in the present study has been, to a greater extent, attributed to the introduction of a methodological change related to body height measurements according ISAK standard. Namely, since 2020, a stretched body height has been measured, in contrast to previous non-stretched measurements performed according to Lohman et al. (Lohman 1988). According to a pilot comparison on a subsample (N=60), the average difference between the two measurements of body height was 0.7 (0.4) in 2023 (unpublished results), thus an increase of 0.7cm, on average, in body height since 2020 can be attributed to a methodological change and the rest to the actual change in body height.

Since changes in physical growth are multidimensional and can be influenced by many factors (socio-economic-political-emotional) (Bogin 2021b), such a result is not surprising. Over the last six decades, Slovenian students have undergone a transition in their environment – from living in Yugoslavia, a country with a state-owned economy, with limited access to global markets (Ferfila 2010) and thus inaccessibility to such a diverse range of food as nowadays (which includes inaccessibility of highly processed food in the past), to the opposite. Namely, Slovenia, a member of the European Union since 2007, has a global market economy with easy access to a wide range of foods – including those containing excessive amounts of sugar and fat. Although the relationship between the

Table 6 Secular trend of different anthropometric characteristics presented as results of simple linear regression with year of measurement as independent variable and each dependent variable, for females.

			Females				
Independent variable		N	B	95% CI	p	R^2 adj.
Body height	[cm]	3311	0.072	0.062, 0.082	<0.001	0.059
Body mass	[kg]	3273	0.062	0.047, 0.076	<0.001	0.019
Anthropometric characteristics for assessing overweight/obesity						
BMI	[kg/m2]	3273	0.003	-0.002, 0.008	0.357	0.000
Waist C	[cm]	2785	0.111	0.099, 0.112	<0.001	0.107
Abdominal SFT	[mm]	1395	-0.007	-0.024, -0.010	0.408	0.000
Triceps SFT	[mm]	3200	0.065	0.056, 0.075	<0.001	0.057
Thigh SFT	[mm]	1391	0.025	0.005, 0.044	0.012	0.004
Anthropometric characteristics for assessing lean body mass						
Upper arm C	[cm]	3250	-0.004	-0.009, 0.001	0.085	0.001
Thigh C	[cm]	1377	-0.110	-0.120, -0.099	<0.001	0.236
UMA	[cm2]	3185	-0.106	-0.120, -0.092	<0.001	0.063
TMA	[cm2]	1262	-0.875	-0.948, -0.801	<0.001	0.300
Anthropometric characteristics for assessing external skeletal robustness						
Width elbow	[cm]	2271	-0.003	-0.004, -0.002	<0.001	0.025
Width knee	[cm]	2223	-0.010	-0.011, -0.008	<0.001	0.093
FI.elbow	[%]	2270	-0.035	-0.040, -0.031	<0.001	0.084
FI.knee	[%]	2222	-0.080	-0.088, -0.073	<0.001	0.174

N – number of subjects, BMI – body mass index, C – circumference, SFT – skinfold thickness, FI.elbow – Frame index according to elbow width, FI.knee – Frame index according to knee width, TMA – thigh muscle area, UMA – upper arm muscle area, R^2 adj. – adjusted R squared, B – unstandardized beta, CI – confidence interval, p – value of statistical significance average body height and socio-economic development was not analysed in our study, this was observed in a study of Negasheva et al. (Negasheva et al. 2024) on Russian adolescents/young adults.

Secular trends in body fat and muscle area

Our results revealed that the increase in average body height was accompanied by a positive trend in average body mass over the same period (1.2kg and 0.6kg per decade for males and females, respectively). However, the observed increase was due to an excessive accumulation of body fat (assessed with SFT) and decrease in muscle area (assessed with UMA and TMA) (especially in females). The positive trend in accumulation of body fat (especially abdominal fat) and decrease in muscle mass is worrying, as it has a negative impact on health, as it can result in metabolic syndrome and insulin resistance even in normal-weight obese young adults (Madeira et al. 2013). In the long term, individuals with normal-weight central obesity had the worst long-term survival rate (Sahakyan et al. 2015) which should be a major cause for concern.

Our results demonstrated a significant increase in the accumulation of body fat in the abdominal area (which was particularly evident from the measure of waist circumference), although in females the average BMI has not changed significantly over time. However, the prevalence of overweight/obesity (according to BMI) increased in both sexes for approximately 8% in males and 4% females, reaching 20.3% and 18.4% in males and females, respectively, in the 2020–23 decade. These results are comparable with those of other countries worldwide. In 19-year-old Polish males, the average BMI increased from 21.7kg/m2 (in the year 1965) to 22.9kg/m2 (in the year 2010), which is still within the normal BMI range (Lipowicz et al. 2015). However, the authors demonstrated, that the prevalence of overweight/obesity (according to BMI) increased from 5.4% to 22.9% over the same period. Furthermore, abdominal obesity (as assessed with waist

Table 7 Secular trend of different anthropometric characteristics presented as results of simple linear regression with year of measurement as independent variable and each dependent variable, for males and females separately.

		Males (N=1464)			Females (N=2160)		
		B	95% CI	p	B	95% CI	p
FI.elbow		R^2 adjusted 0.241, p<0.0001			R^2 adjusted 0.196, p<0.0001		
Body height	[cm]	-0.206	-0.226, -0.186	<0.001	-0.133	-0.152, -0.115	<0.001
Body mass	[kg]	0.147	0.127, 0.168	<0.001	0.062	0.043, 0.082	<0.001
Triceps SFT	[mm]	-0.188	-0.223, -0.154	<0.001	0.010	-0.016, 0.035	0.463
UMA	[cm2]	-0.027	-0.040, -0.014	<0.001	0.057	0.043, 0.071	<0.001
FI.knee		R^2 adjusted 0.354, p<0.0001			R^2 adjusted 0.457, p<0.0001		
Body height	[cm]	-0.247	-0.270, -0.223	<0.001	-0.302	-0.331, -0.272	<0.001
Body mass	[kg]	0.108	0.081, 0.134	<0.001	0.107	0.078, 0.136	<0.001
Thigh SFT	[mm]	0.019	0.013, 0.024	<0.001	0.036	0.031, 0.041	<0.001
TMA	[cm2]	-0.004	-0.030, 0.022	0.765	0.072	0.051, 0.094	<0.001

N – number of subjects, TMA – thigh muscle area, UMA – upper arm muscle area, FI.elbow – Frame index according to elbow width, FI.knee – Frame index according to knee width, R^2 adj. – adjusted R squared, B – unstandardized beta, CI – confidence interval, p – value of statistical significance

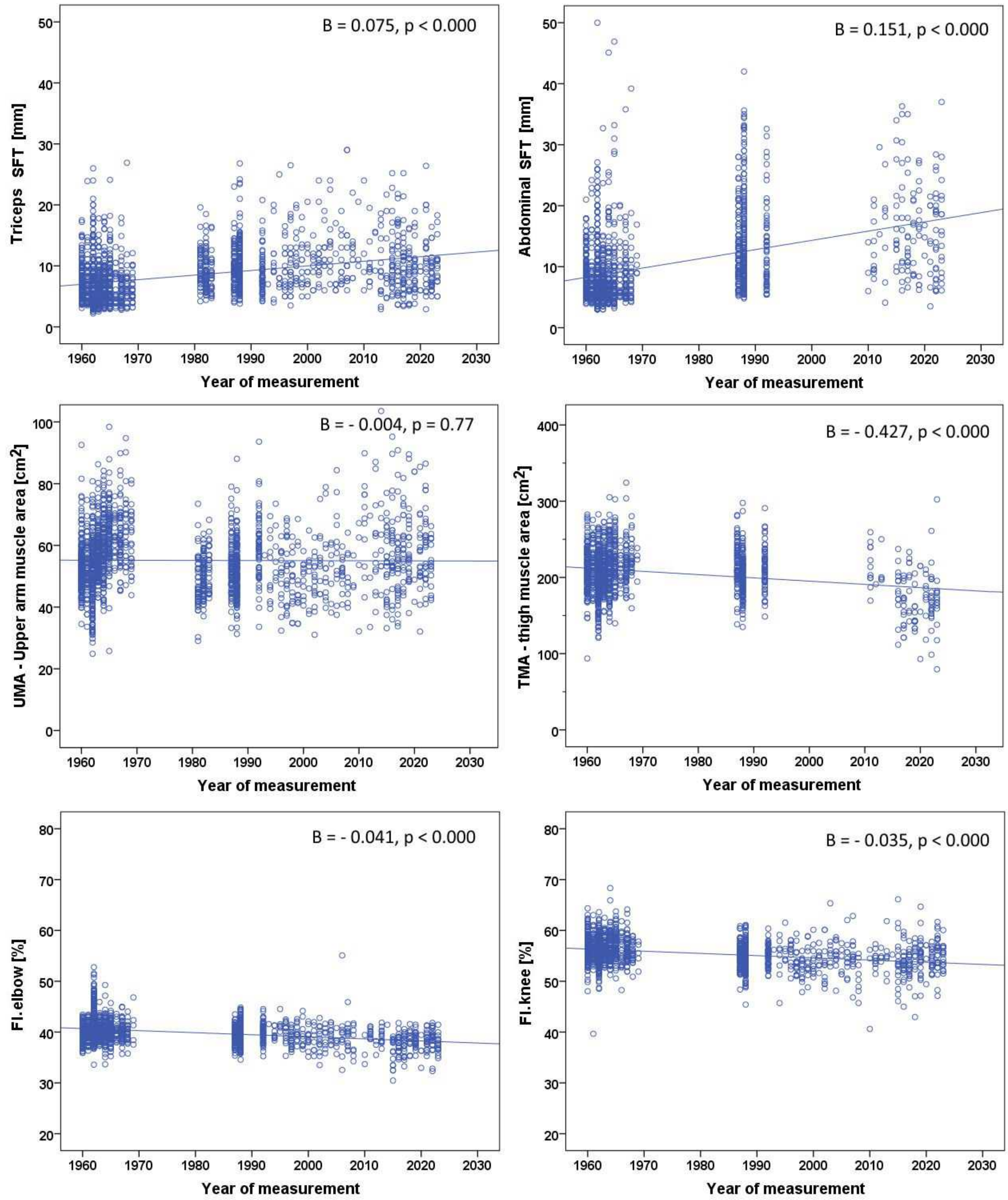

Figure 1 Scatter plots for males showing the correlations between the years of measurements and the selected dependent variable used as a proxy for body fat (i.e. triceps skinfold thickness (SFT) and abdomen SFT), muscle mass (i.e. muscle area of upper arm (UMA) and thigh (TMA)), and external skeletal robustness (i.e. frame index according to elbow width (FI.elbow) and knee width (FI.knee)). In each plot, the p-value and unstandardized beta (B) are indicated.

circumference) increased in both normal weight and overweight adults in the US between 1988 and 2010 (Ladabaum et al. 2014), as well as in Chinese adults between 1993 and 2015 (Sun et al. 2021). In addition, Ladabaum et al. (Ladabaum et al. 2014) associated these findings to an increased prevalence of leisure-time physical inactivity, without a significant change in daily caloric intake. In contrast, the study by

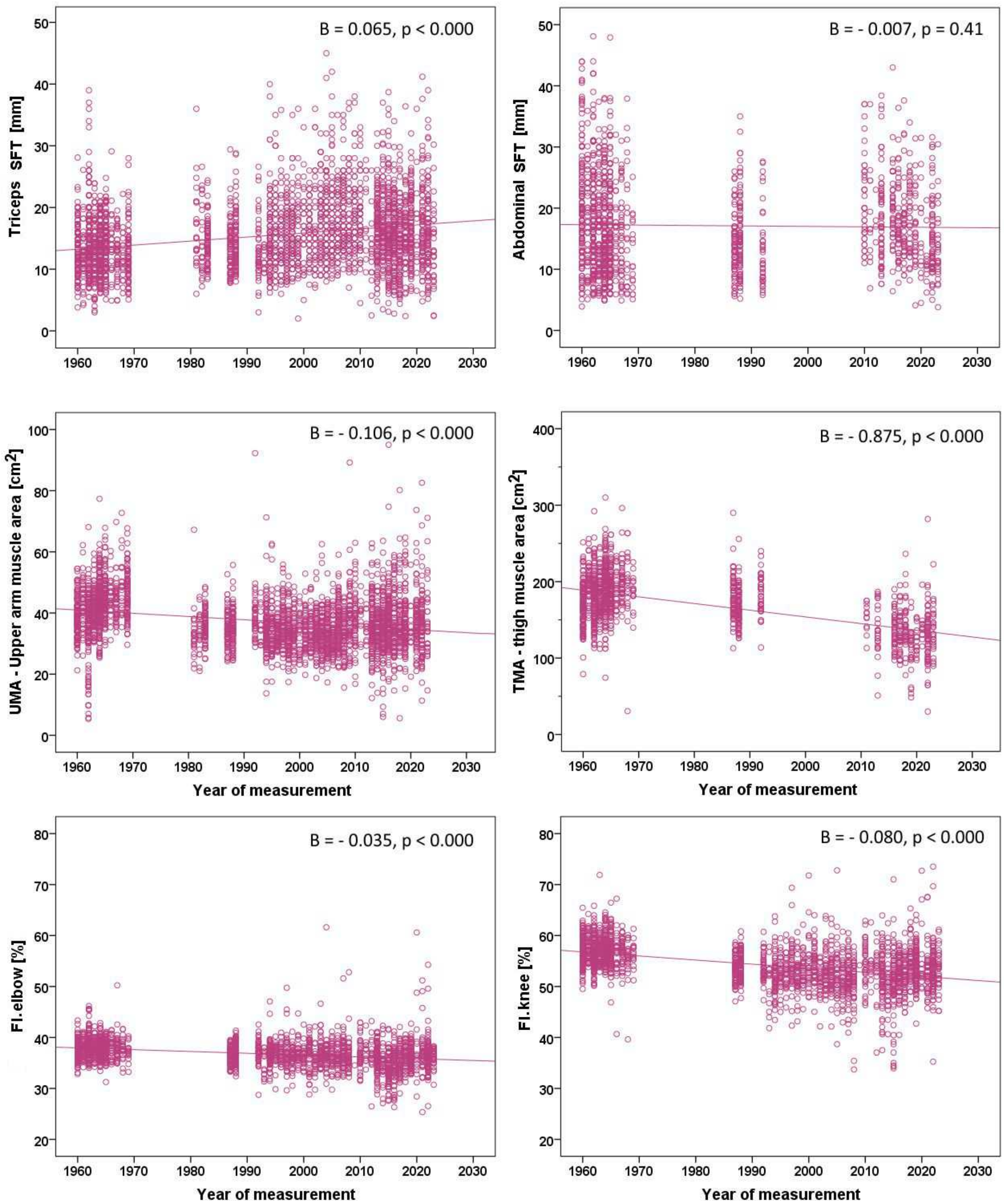

Figure 2 Scatter plots for females showing the correlations between the years of measurements and the selected dependent variable used as a proxy for body fat (i.e. triceps skinfold thickness (SFT) and abdomen SFT), muscle mass (i.e. muscle area of upper arm (UMA) and thigh (TMA)), and external skeletal robustness (i.e. frame index according to elbow width (FI.elbow) and knee width (FI.knee)). In each plot, the p-value and unstandardized beta (B) are indicated.

Brown et al. (Brown et al. 2016), based on NHANES data, found an overall increase in both the caloric intake and self-reported leisure-time physical activity in adults in the US between 1972 and 2008, while an increase in obesity was observed over the same period. Yet, the authors were unable to demonstrate any direct relationships between the caloric intake or leisure-time physical activity and increases in BMI over time (Brown et al. 2016).

In contrast to the increase in body fat in our sample, results of this study showed a decrease in muscle area, particularly in the legs (TMA) in both sexes and in the arms (UMA) in females. To our knowledge, there are no comparable studies in young adults examining the secular trend in UMA and TMA to compare them with our results. However, the study by Stachoń et al. (Stachoń et al. 2012) on the physique of Polish students according to somatotype components demonstrated different results than our present study. According to Stachoń et al. (Stachoń et al. 2012), between 1967 and 2008, the muscle component (mesomorphy) increased in males, while the fat component (endomorphy) did not change. In females, the muscle component remained at a similar level, while the fat component decreased (Stachoń et al. 2012). It is worth noting that the study by Stachoń et al. (Stachoń et al. 2012) was conducted on students from the University School of Physical Education, who may not be representative of the general population, which could be the reason for the discrepancy between their and our results. The study of Đurić et al. (Đurić et al. 2021) in Slovenian children and adolescents (aged 6 to 19) showed that leg muscle power declined over the decades (from 1983 to 2014) in both sexes, which supports the results of muscle area reduction observed in our study. In contrast, arm muscle strength increased over decades in the oldest group (15–19 years) (Đurić et al. 2021). Trends in the amount of moderate to vigorous physical activity (PA) from the Health Behaviour in School-aged Children data from 2002 to 2010 (Kalman et al. 2015) showed a negative trend in Slovenian males and no trend in Slovenian females over the investigated period, which could partly explain the decrease in muscle area in both sexes. Unfortunately, no studies on the secular trend of sports type in young adults (students) have been conducted in the Slovenian population, which might potentially explain the simultaneous decrease in TMA and increase in UMA in males in our sample (or, equivocally, the decrease in leg muscle power and the increase in arm muscle power in the study conducted by Đurić et al. (Đurić et al. 2021)).

Methodological issue associated with the use of BMI

It should be noted that the results of this study point to a methodological issue associated with the use of BMI to assess overweight/obesity in secular trend analyses. In our study, a significant positive secular trend in overweight/obesity in Slovenian young adults was confirmed for most measures used to assess overweight/obesity, such as triceps SFT, abdominal SFT, and thigh SFT, as well as waist C, but not for BMI. Although BMI is commonly used for this purpose, it was not sensitive enough to detect a statistically significant increase in body fat over time, when compared to other measures used in the present study, specifically, SFTs and waist C. The discrepancy could be due to several factors, such as an increase in the subjects' height along with body mass over the generations studied, changes in physical activity or diet. Namely, since BMI does not distinguish between body fat mass and lean body mass, it remained relatively unchanged despite the increase in body fat mass of the subjects. Therefore, the results of the present study point to the use of alternative anthropometric measures to BMI for the assessment of obesity risk in a population, thus measures that are more sensitive in detecting an increased accumulation of peripheral or abdominal fat. According to the results of our present and previous (Zdesar Kotnik and Golja 2012) study, as well as studies by

Kryst et al. (Kryst et al. 2016) and Sun et al. (Sun et al. 2021), waist C is emphasised (in addition to BMI) as a recommended screening tool for abdominal obesity in secular trend analyses. Using waist C as a proxy for obesity has an additional advantage, as the accumulation of abdominal fat has been shown to lead to more severe health problems, as compared to the accumulation of peripheral fat (Choi et al. 2019).

Secular trend in external skeletal robustness

In our study, the external skeletal robustness (assessed with the Frame Index) decreased over the last six decades in young Slovenian adults. There are no similar studies in adults, with which our results could be compared. However, a few studies conducted in children and adolescents on secular trends of external skeletal robustness also showed a decrease in frame index over decades. Namely, this was observed in Argentinian children aged 6 to 14 years between 2001–06 and 2010–16 (Navazo et al. 2020), in German and Russian children aged 6 to 10 years between 2000 and 2010 (Rietsch et al. 2013a), in German children and adolescents aged 3 to 18 years between 1980 and 2012 (Scheffler and Hermanussen 2014). Different studies suggested different associations for poorer/greater external skeletal robustness. First, most studies found a positive association between BFP and the external skeletal robustness as measured with the body frame size (Martinez et al. 1995; Leonard et al. 2004; Musálek et al. 2018; La Guzmán-de Garza et al. 2017; Rietsch et al. 2013a; Vispute et al. 2023; Lizana and Hormazabal-Peralta 2020), while others found the opposite (Musálek et al. 2018; Scheffler 2010). Similarly, a systematic review and meta-analysis by Deng et al. (Deng et al. 2021), which focused on bone mineral density, showed a negative effect of BFP on bone mineral density. Second, the same review (Deng et al. 2021) showed that higher lean body mass is associated with higher bone mineral density. Third, a study by Glauber et al. (Glauber et al. 1995) on US adults demonstrated that the most important factor (besides BFP assessed with bioimpedance analysis and waist-to-hip ratio) associated with higher bone mineral density, was body mass, especially for the mass-bearing bones. Our results are partially consistent with the latter. In our multivariate regression model, body height and body mass together explained most of the variance of external skeletal robustness, with body height having the highest negative correlation with FI.elbow and FI.knee, and body mass having the highest positive correlation with both indices in both sexes. The observed decrease of external skeletal robustness in our sample can at least partly be explained with a decrease in muscle mass due to reduced physical activity, which, in combination with adequate nutrition, is the most important factor for building healthy strong bones (Proia et al. 2021). However, data on bone mineral density would be more accurate for studying the effects of physical activity (or body fat) on skeletal robustness.

The results of the present study suggest that significant changes in the economy and lifestyle in Slovenia are reflected in changes in body dimensions and body composition of university students. We observed a significant increase in body height and body fat accumulation (both peripheral and abdominal). Concurrently, there is a documented decrease in muscle area, particularly in the legs, and in external skeletal robustness. It is now well established that changes in body composition, such as the accumulation of body fat and the decrease in muscle mass due to physical inactivity, increase health risks even in young adults in normal-weight category according to BMI (but obese according to BFP) (Bowden Davies et al. 2019; Correa-Rodríguez et al. 2020).

Some limitations of the study should, of course, also be noted. Firstly, different measurements are missing for different time periods, so the sample size is rather small for some decades. Secondly, measuring devices changed over the years (different devices from different manufacturers were used) and different examiners were responsible for the measurements over time, which was inevitable due to the comprehensive longitudinal aspect of data collection. However, since each examiner was trained directly by his or her predecessor, the inter-examiner variability must have been significantly reduced. Finally, regarding the representativeness of the sample, our department is the only one of its kind in Slovenia, so the students participating in our program (and thus in the present study) came from all over the country, from both rural and urban areas. Furthermore, no selection was made based on students' physical abilities prior to their enrolment. Therefore, it seems reasonable to believe, that the results of the present study can indeed be considered representative for the population of university students in Slovenia. We therefore believe that although our study may not have been able to describe the changes in anthropometric characteristics for the whole young adult's country population, it did manage to describe the changes occurring over the last six decades in our country in the student population with scientific credibility. Moreover, the data presented come from six different decades and provide a rare insight into the anthropometric characteristics and their secular trends in young adults from a transitional society. They also demonstrate the influence of anthropometric characteristics on the external skeletal robustness, which has so far been only studied in children and adolescents.

Conclusions

Over the past six decades positive secular trends include an increase in body height and an accumulation of body fat, while negative secular trends include a decrease in muscle mass and external skeletal robustness in Slovenian young adults (students). These changes appear to have parallel but possibly independent patterns in the broader context of secular trends in body characteristics. The observed changes can be attributed to the economic transition to a global market with easy access to a wide range of foods, including those containing excessive amounts of sugar, and changes in lifestyle from more active to more sedentary in recent decades. In particular, the simultaneous increase in SFT as proxy of body fat and decrease in UMA and TMA as proxy of muscle mass in young adults is of great concern. It is crucial to address these effects together, as they both increase health risks already in young adults. Immediate actions and interventions in lifestyle changes should be implemented to reverse these trends. Furthermore, the results of the present study emphasise the importance of monitoring obesity with a measure such as waist circumference in addition to BMI, as BMI fails to exert sufficient sensitivity for the detection of overweight/obesity.

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