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Analysis of periodontal disease in the archaeological population of Dąbrówki (Poland) (16th–17th centuries)

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Abstract

Introduction
Periodontitis is a disease affecting a significant proportion of both modern and historical populations, and its development is largely associated with poor oral hygiene.

Study aim
The aim of this study was to assess periodontal status of the historical population of Dąbrówki (Poland), dated to the 16th–17th centuries.

Material and Methods
The study sample consisted of dental material from 24 individuals (12 females and 12 males), divided into three age groups (17–25, 26–35, and >36 years). The analysis was based on measurement of the distance between the cementoenamel junction and the surface of the alveolar bone, assessment of changes in the mesial and distal interdental septa, evaluation of architectural changes in the alveolar bone, and assessment of the possible presence of molar furcation.

Results: Periodontitis was diagnosed in 75% (18/24) of the examined individuals, and pathological changes were identified in 28% (146/520) of the analysed teeth. The occurrence of the disease was related to sex, with periodontitis being statistically more frequent in males (46%) than in females (12%). An increase in disease severity with age was also observed.

Conclusions: The results indicate that the population of Dąbrówki exhibited a lower frequency of periodontitis than other Polish populations from a similar historical period. One possible explanation is the rural character of the community, where dietary patterns may have differed from those of urban populations. Research on the Dąbrówki population is ongoing, and further analyses, including isotopic studies, are expected to allow a more comprehensive interpretation of the findings.

Keywords: periodontitis, dental material, ancient Poland, oral hygiene, diet

Original article

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Introduction

Periodontal disease is a persistent inflammation of the tissues that make up the periodontium, which may include the gums, alveolar bone, root cementum, and periodontal ligament (e.g., AAP, 2003; Armitage, 2004; Ogden, 2008). Periodontal diseases are divided into gingivitis and periodontitis. Gingivitis results from plaque accumulation, which leads to inflammation of the soft tissues around the tooth; this condition is reversible (e.g., Trombelli, 2025). Periodontitis, on the other hand, is an advanced form of the disease in which permanent damage to the periodontal structures occurs. Periodontal disease affects a significant proportion of the population worldwide. It is estimated that more than 42% of adults aged >30 years suffer from some form of gum disease, and nearly 8% have severe periodontal disease (e.g., Nascimento et al., 2024). In many individuals, the disease leads to tooth loss due to reduced stability and damage to the alveolar bone (Armitage, 1999; Highfield, 2009).

The main cause of periodontal disease is poor oral hygiene. As the disease progresses, anaerobic bacteria such as *Porphyromonas gingivalis* and *Prevotella intermedia* gradually replace the natural saprophytic microflora of a healthy mouth. Substances produced by these bacteria trigger an inflammatory response in the body, leading to damage to the tissues surrounding the tooth (Czerniuk et al., 2016; Li et al., 2025; Mehrinia & Van Dyke, 2026; Nazir, 2017; Pihlstrom et al., 2005). Some authors attribute periodontal disease to dietary habits, such as vitamin or micronutrient deficiencies (e.g. Garcia et al., 2001). Studies by Šlaus et al. (1997) suggest that greater access to highly cariogenic foods contributes to periodontal disease. However, the role of diet in periodontal disease remains under discussion (e.g. Balice et al., 2025). Other causes have also been identified; metabolic disorders, such as diabetes or insulin resistance, can exacerbate inflammatory processes in periodontal tissues (e.g. Saito & Shimazaki, 2007). In addition, excessive and chronic psychological stress (Aleksejūnienė et al., 2002; Genco et al., 1999) and the use of stimulants, such as smoking (Nociti et al., 2015), are recognised as contributing factors to periodontitis.

Studies of periodontitis are rarely conducted on historical populations because they require well-preserved teeth and dental arches (e.g., Karkus, 2018; Vodanović et al., 2012). Because of the disappearance of soft tissues after death, analyses of periodontal disease are usually limited to assessing the presence or absence of periodontitis in individuals (e.g., DeWitte & Bekvalac 2011; Kwiatkowska & Nowakowski, 2011; Oztunc et al., 2006). Other aspects, such as disease severity, are therefore often omitted. Nevertheless, studies of historical populations are valuable because they provide insight into the hygiene and dietary practices of past communities.

The most recent excavations, conducted between 2022 and 2024 at the Dąbrówki site in Poland, provide an opportunity to analyse this population with respect to periodontal disease and to use the resulting data to reconstruct local dietary and hygiene habits. The key research questions address the following issues: (i) What was the incidence rate of periodontal disease in the Dąbrówki population compared with other groups in Poland? (ii) Are there differences in incidence between the sexes? (iii) Can stages of disease progression be identified in the studied population?

Material and methods

The material used for this research derives from a cemetery in Dąbrówki, Podlaskie Province, Poland (Fig. 1). The cemetery was probably established for the burial of the local rural population. Because of the rare mention of rural burials in written sources, this cemetery – like most sites of this type – was discovered accidentally during construction work carried out in the vicinity of the village. Nevertheless, a small number of historical sources refer to the settlement as a place associated with Queen Bona and Sigismund Augustus (Wawrzeniuk, 2021). In several graves, artefacts were recovered (e.g. a silver coin bearing the image of Sigismund III Vasa dated to 1593), allowing for a preliminary dating of the cemetery to the 16th and 17th centuries. Radiocarbon (^{14}C) dating indicates that the burials date to the period 1505–1615 AD (Wawrzeniuk et al., 2023).

During the archaeological investigations, 62 graves were uncovered. However, because of the quality of preservation – particularly in the dental arch region – and the possibility of reliable sex and age determination, only 24 adult individuals (12 males and 12 females) were ultimately included in the analysis. In total, 520 permanent teeth were examined (226 anterior and 294 posterior). Only fully erupted teeth with antagonists in the opposing dental arch were included in the analysis (Table 1).

Figure 1. Map illustrating the location of the archaeological site in Dąbrówki

The sex of individuals was determined on the basis of pelvic bone morphology as well as cranial traits, in accordance with the scoring system for sexually dimorphic cranial features proposed by Buikstra and Ubelaker (1994). Age at death was estimated using changes in the topography of the auricular surface of the ilium and morphological characteristics of the pubic symphysis.

Table 1. The number of teeth analysed in this study

Maxilla																
FDI	11	12	13	14	15	16	17	18	21	22	23	24	25	26	27	28
No.	14	15	19	17	18	16	10	8	13	15	19	17	14	11	12	9
Mandible																
FDI	31	32	33	34	35	36	37	38	41	42	43	44	45	46	47	48
No.	22	22	23	21	19	14	18	8	20	22	22	21	18	13	17	13

FDI World Dental Federation (Fédération Dentaire Internationale, FDI)

Given the correlation between the incidence of periodontal disease and age, the sample was divided into three age categories: 17–25, 26–35, and >36 years. A similar age division has been used in previous research, allowing for comparability with other studies (Tomczyk et al., 2018).

The American Academy of Periodontics (AAP) and European Federation of Periodontology (EFP) indicate that the severity of periodontitis should be determined based on clinical attachment loss, pocket depth, bleeding on probing, and bone loss. According to these criteria, a patient has periodontitis when these symptoms are diagnosed (e.g., Chmielewski et al., 2025). However, the criteria cannot be used in the diagnosis of individuals from historical populations. Therefore, other methods of identifying periodontal disease and its severity are proposed. The following criteria were used for a reliable assessment of the presence of periodontal disease:

I. Measurement of the distance between the cementoenamel junction (CEJ) and the surface of the alveolar crest (AC). Measurements were taken using callipers and recorded in millimetres (accuracy: 0.01 mm). A CEJ–AC distance of 3 mm is generally regarded as normal, whereas a distance of >3 mm is considered indicative of a lesion (e.g. Shaju, 2011).

II. Assessment of changes in the mesial and distal interdental septa (interproximal bone) of each tooth. Observations were made at 10× magnification under standardised lighting conditions using an endodontic microscope (Global Surgical Corporation, USA). Findings were recorded as the presence (1) or absence (0) of the interdental septum.

III. Evaluation of changes in the texture and architecture of the alveolar bone. For this criterion, the method proposed by Kerr (1988) was applied, with modifications introduced by our research team (Tomczyk et al., 2017). This classification allows the severity of periodontitis to be identified and divided into mild (early), moderate, and severe (advanced) stages.

IV. In cases where bi- or trifurcation of the root was exposed, the presence (1) or absence (0) of furcation involvement was assessed using a periodontal probe.

Periodontal disease was diagnosed only when all three criteria (i–iii) were met for anterior and posterior teeth. The fourth criterion (iv) was additionally introduced in accordance with the newest American Academy of Periodontics (AAP) and European Federation of Periodontology (EFP) recommendations for diagnosing moderate and advanced stages of periodontal disease (e.g., Chmielewski et al., 2025).

The presence of dental calculus was treated as an additional, but not essential, criterion for evaluation (e.g. Lieverse, 1999; Vodanović et al., 2012), as calculus on archaeological material may be easily damaged or lost during excavation, handling, or transport to the laboratory.

Statistical analyses were conducted using the R Project for Statistical Computing (version 4.3.1). Two-sample and three-sample tests of proportions were applied to identify significant differences between age groups and between females and males. Tables 2 and 3 report the chi-square test statistics and corresponding p-values. Differences with $p \leq 0.05$ were considered statistically significant.

Results

The study included a total of 24 individuals (12 males and 12 females) with well-preserved dental and skeletal material. Pathological changes were identified in 18 individuals (9 males and 9 females), accounting for 75% of the analysed sample. In total, 520 teeth were examined, including 226 anterior and 294 posterior teeth. Evidence of periodontal disease was observed in 146 teeth (28%), of which 55 (24%) were anterior teeth and 91 (31%) were posterior teeth.

The results indicate variation in disease incidence across age groups. In the 17–25-year age group, periodontal disease was least frequent, affecting only 9% of the teeth examined. The highest prevalence was recorded in the 26–35-year age group, in which periodontal disease was identified in 44% of teeth; in this group, the disease occurred exclusively in males. Among individuals aged over 36 years, the prevalence of lesions was 39% and was significantly higher in males (45%) than in females (16%). Regardless of age group, periodontal disease was statistically more common in males (Table 2).

Because disease severity is likely to be related to age, this relationship was examined in the next stage of analysis (Fig. 2). Across all age groups and in both sexes, moderate periodontal disease was the most frequently observed stage. However, a marked increase in advanced disease was noted between the youngest (17–25 years) and middle (26–35 years) age groups (5% versus 30%) (Table 3).

Figure 2. Different stages of periodontal disease progression (marked with black arrows where present) observed in the population from Dąbrówki (A – healthy, B – early stage, C – moderate stage, D – advanced stage)

Differences in susceptibility to periodontal disease were also observed between the sexes. Among males aged 26–35 years, the moderate stage of periodontal disease predominated (40% versus 33%), whereas among females in the same age group, the early stage was most common (47% versus 27%) (Table 3).

Table 2. Prevalence of periodontitis by age group

Age of individual	Total	Male	Female	p	χ^2
17–25	19/212 (9%)	7/73 (10%)	12/139 (9%)	1	1.7
26–35	67/154 (44%)	52/52 (100%)	15/102 (15%)	<0.0001	101.9
>36	60/154 (39%)	55/123 (45%)	5/31 (16%)	0.014	8.508
p	0.0001	0.0001	0.3032		
χ^2	65.55	100.1	2.39		
Total	146/520 (28%)	114/248 (46%)	32/272 (12%)	<0.0001	75.1

Table 3. Progression of periodontitis by age group

Age of individual	Total			Male			Female		
	Early	Moderate	Advanced	Early	Moderate	Advanced	Early	Moderate	Advanced
17–25	2/19 11%	16/19 84%	1/19 5%	–	7/7 100%	–	2/12 17%	9/12 75%	1/12 8%
26–35	21/67 31%	26/67 39%	20/67 30%	14/52 27%	21/52 40%	17/52 33%	7/15 47%	5/15 33%	3/15 20%
>36	22/60 37%	33/60 55%	5/60 8%	22/55 40%	31/55 56%	2/55 4%	–	2/5 40%	3/5 60%
p	0.098	0.002	0.002	0.220	0.008	0.0002	0.218	0.088	0.062
χ^2	4.64	12.75	12.36	1.50	9.68	13.52	1.51	4.86	5.57

In the diagnosis of periodontitis, particular attention is often paid to measurements of the distance between the CEJ and the AC. The present study shows that this distance increases with disease progression. The lowest values (mean: 2.5 mm) were recorded in the healthy group, while mean measurements increased progressively in subsequent stages of the disease. An accompanying increase in standard deviation was also observed, indicating greater variability in CEJ–AC distances in more advanced stages of periodontitis (Table 4).

Table 4. Disease progression and measurements between the cementoenamel junction and the alveolar crest

Stage of periodontitis	min	max	mean	median	SD
Healthy	1.0	7.1	2.5	2.2	1.06
Early	3.2	7.1	4.5	4.2	0.93
Moderate	4.0	9.6	6.3	6.1	1.13
Advanced	5.0	12.0	8.0	7.8	1.51

Discussion

The population studied from the Dąbrówki site shows a frequency of periodontal disease, in terms of the number of affected individuals, similar to that reported for other populations from Poland dated to a comparable historical period (16th–17th centuries) (Table 5). It may therefore be assumed that the environmental factors most commonly associated with periodontal disease, such as diet quality and oral hygiene, were broadly similar in the populations considered. However, it should be noted that apparent similarities in disease frequency may also result from differences in diagnostic methodology. In many earlier studies, authors relied on only one or two diagnostic criteria, such as visual assessment of alveolar bone resorption, the presence of dental calculus (Gleń, 1976), or CEJ–AC measurements alone (Kozubkiewicz & Trachtenberg, 1960). As a result, their estimates may be overstated. Only studies of the populations from Brześć Kujawski (Karkus, 2018) and Radom (Tomczyk et al., 2018) applied methods comparable to those used in the present research. For this reason, comparisons were limited to these two Polish populations.

Analysis of data from the chronologically similar populations of Brześć Kujawski and Radom (16th–17th centuries) suggests that the proportion of teeth affected by periodontal disease in the Dąbrówki population was relatively low (28%).

Table 5. Prevalence of periodontitis in historical populations from Poland

Period	Site	Individuals	References
15^{th}-18^{th}	Brześć Kujawski	48/61 (79%)	Kozubiewicz & Trachtemberg 1960
14^{th}-17^{th}	Brześć Kujawski	37/48 (77%)	Karkus 2018
15^{th}-18^{th}	Cracow	68/108 (63%)	Gleń 1976
16^{th}-18^{th}	Wrocław	18/30 (60%)	Kwiatkowska & Nowakowski 2011
14^{th}-17^{th}	Radom	57/80 (71%)	Tomczyk et al. 2018
18^{th}-19^{th}	Radom	93/126 (74%)	Tomczyk et al. 2018
16^{th}-17^{th}	Dąbrówki	18/24 (75%)	presented publication

In Brześć Kujawski, pathological changes were identified in 41% of examined teeth (Karkus, 2018), while in the population of Radom, dated to the late Middle Ages and early modern period (14^{th}–17^{th} centuries), periodontal disease was diagnosed in 44% of teeth (Tomczyk et al., 2018). The observed differences between the Dąbrówki population and the groups from Brześć Kujawski and Radom may be related to differences in socio-economic status. The population examined in the present study derives from a rural context, whereas the populations from Brześć Kujawski and Radom were associated with urban centres. Comparative studies indicate that during the late Middle Ages and early modern period, urban populations generally exhibited poorer oral health, which has been linked, among other factors, to diets richer in highly processed carbohydrates (e.g., Šlaus et al., 1997; Tomczyk et al., 2018). These factors may therefore help explain the higher incidence of periodontal disease observed in the urban populations. At the current stage of research, no independent data are available to confirm the quality or composition of the diet in the Dąbrówki population, as analyses of the material are still ongoing. By contrast, detailed studies conducted at the Radom site, including isotopic, archaeozoological, and archaeobotanical analyses, confirm the proposed pattern, namely that urban populations had poorer diets and a higher proportion of individuals affected by diseases of the masticatory system (Tomczyk et al., 2018; 2020).

Of course, it should be remembered that periodontitis is a multifactorial disease (e.g., Muro et al., 2026). Its development may be influenced by behavioural factors (lifestyle), nutritional factors, or metabolic disorders (such as diabetes or insulin resistance). However, the interpretation of results based on bone (archaeological) material is always limited to those elements that can be verified by scientific evidence. Therefore, when looking for the causes of periodontal disease in historical populations, the most common factors pointed to are diet quality and the socioeconomic status of the population studied.

The results obtained for the Dąbrówki population also reveal a clear contrast between males and females in the prevalence of periodontitis. Contemporary studies consistently show that periodontal disease is more common in men than in women (e.g., Ioannidou, 2017; Stănescu et al., 2020), and similar patterns have been documented in historical populations (e.g., Karkus, 2018; Novak, 2015; Raitapuro-Murray et al., 2014). Sex is considered a potential risk factor, as the composition of the oral microbiome differs between women and men, and sex hormone levels – particularly male androgens – may influence the development and progression of periodontal disease (e.g., Del Pinto et al., 2024; Mascarenhas et al., 2003). Clinical studies further indicate that oestrogen slows the production of inflammatory cytokines, such as interleukin-1β and tumour necrosis factor-α, which are responsible for bone resorption during periodontal inflammation. As a result, women tend to produce fewer cytokines in response to infection. Progesterone also plays an important role in the formation of periodontal ligaments and the maintenance of bone mass (e.g., Ahmed et al., 2010). These biological mechanisms may help explain the lower incidence of periodontal disease observed among women.

Dietary factors may also have contributed to sex-related differences in disease prevalence. Research by Reitsema et al. (2010) indicates that males in historical populations more frequently consumed meat products. Diets rich in protein are thought to promote dental calculus accumulation (Hillson, 1979), as increased protein intake leads to elevated blood urea levels. Oral bacteria metabolise urea into ammonia, resulting in increased oral alkalinity (Lieverse, 1999) and, consequently, greater calculus formation. These processes may provide an additional explanation for the significantly higher prevalence of periodontitis observed among males from Dąbrówki.

When discussing periodontal disease, the relationship between age and disease severity must also be considered. Periodontitis develops gradually, with its effects accumulating over time (e.g., Benatti et al., 2009; Flemmig, 1999). In the Dąbrówki population, a clear progression was observed between successive age groups (9% versus 44%). In the oldest age group, however, the prevalence of disease decreased to 39%. This phenomenon has been described in previous studies and is likely related to tooth loss in individuals affected by the most advanced stages of periodontitis (DeWitte & Bekvalac, 2011). With increasing age, changes in immune function may further exacerbate chronic inflammation and contribute to declining oral health (Lopez et al., 2017; Preshaw et al., 2012). Notably, disease progression appeared to occur more rapidly in males. In the 26–35-year age group, 40% of males were diagnosed with moderate periodontitis and 32% with advanced disease, whereas among females of the same age, 33% exhibited moderate disease and 20% advanced disease.

In odontological research, the use of multiple diagnostic criteria is essential. For many years, CEJ–AC measurement was the primary method for assessing periodontitis in skeletal material (e.g., DeWitte, 2012; Kozubkiewicz & Trachtenberg, 1960; Raitapuro-Murray et al., 2014). It is now recognised, however, that this criterion alone is insufficiently reliable and may lead to misdiagnosis (e.g. Tomczyk et al., 2017). Recent studies (e.g., Muro et al., 2026) suggest that macromorphological bone defects provide a more robust indicator of periodontal disease. For example, research conducted on a forensic collection from Yucatán demonstrated that bone changes were present in 94.8% of individuals, whereas CEJ values exceeded diagnostic thresholds in only 55.8% (Muro et al., 2026). Reliance solely on CEJ measurements would therefore result in substantial underestimation of disease prevalence. Although CEJ values correlate with disease severity, several authors emphasise that this measure should be used as a supportive tool rather than as a primary diagnostic criterion (Muro et al., 2026; Tomczyk et al., 2017). In the Dąbrówki population, the progressive increase in mean CEJ values across disease stages (Table 4) indicates that this measure retains comparative value, but it should be applied in conjunction with the assessment of bone defects to ensure diagnostic reliability and a more comprehensive interpretation of periodontal changes.

Limitations

The main limitation of the present study is the relatively small number of individuals included in the analysis. However, as noted above, research on periodontal disease requires not only well-preserved alveolar bone but also the presence of opposing teeth, which substantially restricts sample size in archaeological contexts.

Conclusions

Periodontal research is rarely represented in anthropological literature, largely because of the condition of preserved skeletal material. Additional challenges arise from the difficulty of accurately diagnosing periodontal disease in archaeological populations. Consequently, each contribution in this area is valuable because it can provide important insights into the dietary practices and hygiene habits of historical communities.

Although examinations of periodontal disease cannot always be conducted because of the preservation state of archaeological material, they can yield informative and meaningful results. The study of the Dąbrówki population indicates a lower frequency of periodontitis compared with other Polish populations from a similar historical period, a pattern that may be linked to the rural character of the community. Nevertheless, further research is required to confirm this interpretation. As discussed, the principal limitation of the study lies in the limited number of individuals analysed; however, this constraint is inherent to periodontal research, which depends on the preservation of both alveolar bone and opposing teeth.

Author contributions

MR conducted research, wrote the article; MZ analysed data and conducted statistical analyses, wrote the article; JT was responsible for research concept and design, critical revision of the article, and final approval of the article.

Ethics statement

The human remains are curated at the Institute of Biological Sciences, Cardinal Stefan Wyszynski University. Research on the presented material did not require ethics committee approval.

Data availability statement

Data are available from the corresponding author upon reasonable request.

Financial disclosure

No funding was received for this study.

Conflict of interest

Co-author Jacek Tomczyk is the President of the Polish Anthropological Society (Polskie Towarzystwo Antropologiczne) of which Anthropological Review is a flagship journal. He was not involved in the editorial handling of this article.

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Understanding global dementia burden: Ageing and dairy supply as key predictors of total, male and female dementia incidence

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Abstract

Introduction

Dementia incidence is rising worldwide, driven largely by population ageing and demographic transition. Although dietary factors have been proposed as modifiable contributors, the role of dairy consumption remains unclear, with inconsistent findings across regions, populations, and product types.

Study aim

This study examined whether total dairy supply independently predicts dementia incidence at the population level after accounting for key demographic and socioeconomic indicators.

Materials and methods

A global ecological analysis was conducted using data from 204 countries. Variables included dairy supply, dementia incidence (total, male, and female), ageing, gross domestic product adjusted for purchasing power parity (GDP PPP), Biological State Index, and urbanisation. Statistical analyses included Pearson and Spearman correlations, partial correlations, principal component analysis, and multivariable linear regression. Enter models were treated as the primary analyses, while stepwise regression was used as an exploratory model-reduction approach.

Results

Dairy supply showed significant positive correlations with total dementia incidence ($r = 0.54$, $p < 0.001$) and with both male and female dementia incidence ($r = 0.53$, $p < 0.001$). Ageing showed the strongest associations across all outcomes ($r = 0.73–0.78$). In the primary multivariable models, ageing remained

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the strongest independent predictor of total, male, and female dementia incidence. After adjustment, dairy supply remained an independent predictor, with modest effect sizes for total ($\beta = 0.209$, $p < 0.001$), male ($\beta = 0.190$, $p = 0.001$), and female ($\beta = 0.223$, $p < 0.001$) dementia incidence. Urbanisation and genetic vulnerability were associated with dementia incidence at the bivariate level but were not independent predictors in the adjusted models. Exploratory stepwise analyses showed a similar pattern.

Conclusions
Ageing remained the strongest global predictor of dementia incidence, while dairy supply showed an additional independent association. These findings suggest that nutritional transitions may interact with demographic ageing to shape global dementia patterns worldwide.

Keywords: dairy supply, ecological study, ageing, socioeconomic development, biological state index, urbanisation, global nutritional transition

Introduction

Dementia is a rapidly growing global health crisis. In 2021, 57 million people were living with dementia as estimated by The World Health Organization (WHO, 2025a). Nearly 10 million new cases occur annually, and this number will triple by 2050 as populations continue to age (Nichols et al., 2022; WHO, 2025a). Dementia is characterised by cognitive decline affecting memory, reasoning, and behaviour, leading to disability, dependency, and substantial social and economic burden (Cipriani et al., 2020; WHO, 2025a). Although ageing remains the most important non-modifiable risk factor, increasing attention has focused on modifiable determinants, including diet, that may influence dementia onset and progression (Lourida et al., 2019).

Diet has gained prominence because of its potential neuroprotective or neurodegenerative effects (Xu Lou et al., 2023; Yassine et al., 2022; You, 2025c; You & Feng, 2025). Dairy products are heterogeneous and include both fermented and non-fermented forms. They provide proteins, minerals, vitamins, and essential amino acids that may support cognition through neurotransmitter synthesis, neuronal integrity, and vascular health (Camfield et al., 2011; Otaegui-Arrazola et al., 2014). Fermented dairy products, such as yogurt and cheese, may contain anti-inflammatory and antioxidant bioactive compounds that reduce neuroinflammation and improve gut–brain interactions (Anderson & Alpass, 2024; Gao et al., 2025a; 2025b). By contrast, high-fat dairy products may adversely affect cognition through hyperinsulinemia, endothelial dysfunction, oxidative stress, and systemic inflammation (Tan & Norhaizan, 2019; Villoz et al., 2024). Thus, the association between dairy intake and dementia may differ according to product type and composition (Camfield et al., 2011).

Previous findings have been inconsistent. A meta-analysis of 15 cohort studies involving more than 300,000 participants reported a nonlinear inverse association between dairy intake and cognitive decline or dementia, with the lowest risk observed at around 150 g/day. The association was stronger among participants aged under 65 years (RR = 0.88, 95% CI: 0.76–1.01) than among those aged 65 years and older (RR = 0.95, 95% CI: 0.75–1.21) (Villoz et al., 2024). Studies including both sexes showed an inverse association (RR = 0.85, 95% CI: 0.78–0.93), whereas sex-specific findings were more heterogeneous, and subtype analyses suggested different patterns for milk and cheese (Villoz et al., 2024). The same meta-analysis also reported an overall inverse association when all dairy types were combined (RR = 0.89, 95% CI: 0.83–0.95). Subtype analyses suggested a null association for milk at ≤0.3 times/day, with lower risk at higher intakes, and a nonlinear pattern for cheese, with lower risk around 0.3 times/day and null or positive associations at higher intakes (Villoz et al., 2024). Another meta-analysis also reported that higher dairy intake may be associated with lower risk of cognitive decline or dementia, although findings varied by sex, age, region, and dairy type (Lee et al., 2018; Villoz et al., 2024). Studies in Asia showed a stronger inverse association than studies in Europe (Villoz et al., 2024). European populations generally consume more dairy (170–711 g/day) than Asian populations (29–165 g/day), despite increasing dietary Westernisation in Asia (Suzuki et al., 2024; Villoz et al., 2024). Recommendations also differ, with Asian guidelines typically suggesting 1–4 servings per day compared with 2–4 servings in Europe, highlighting the importance of cultural and nutritional context (Cámara et al., 2021; Villoz et al., 2024).

Evidence from specific dairy products also supports treating dairy as a heterogeneous exposure. In UK Biobank, Deng et al. reported that soy milk consumption was associated with a lower risk of all-cause dementia (HR = 0.69, 95% CI: 0.54–0.90) and Alzheimer's disease (HR = 0.70, 95% CI: 0.51–0.94), whereas other milk types did not show the same clear pattern (Deng et al., 2023). Emerging evidence also suggests potential cognitive relevance of probiotic dairy products. Kasselman et al. found that older adults reporting daily yogurt/dairy consumption had higher cognitive test scores than non-consumers (40.03 ± 0.64 vs. 36.28 ± 1.26, $p = 0.017$), although this association was attenuated after adjustment for sociodemographic factors ($p = 0.074$) (Kasselman et al., 2024). Together, these findings reinforce the importance of considering dairy as a heterogeneous exposure, as different dairy products may relate differently to cognitive health.

Many studies have examined individual dairy components, often cheese, in relation to cognitive decline (Villoz et al., 2024). Although this approach provides useful mechanistic insight, it does not fully reflect dietary behaviour, as people typically consume multiple dairy products such as milk, cream, butter, yogurt, and cheese (Lourida et al., 2013; Vauzour et al., 2017). Focusing on one component may therefore underestimate the combined effects of overall dairy consumption. Consequently, total dairy consumption, or total dairy supply, may provide a more realistic indicator of population-level dairy exposure (Comerford et al., 2021; Villoz et al., 2024). However, because total dairy supply is analysed as a single aggregated exposure, it cannot distinguish potentially divergent effects of fermented and non-fermented dairy products or low-fat and high-fat dairy products. This heterogeneity should be considered when interpreting any observed associations.

Mediterranean and MIND dietary patterns have shown protective associations with cognitive health through higher intake of plant-based foods and healthy fats and lower consumption of red and processed meats (Chen et al., 2023; Fekete et al., 2025). These patterns also incorporate fermented and low-fat dairy in moderation, suggesting that both type and quantity may influence cognitive outcomes (Morris et al., 2015; Wade et al., 2020). Greater cortical thickness in Alzheimer's-vulnerable regions among individuals adhering to Mediterranean-style diets further supports a neuroprotective role, while dietary responses may also vary by genetic susceptibility, with nutrient effects differing between APOE4 and non-APOE4 carriers (Mosconi et al., 2014; Norwitz et al., 2021; Yassine & Finch, 2020).

Economic affluence and urbanisation may influence dementia incidence and prevalence through multiple, and sometimes opposing, pathways. Lower socioeconomic position is associated with greater dementia risk, whereas age-specific dementia incidence has declined in many high-income countries, possibly reflecting improvements in education, public health, and vascular risk control. Evidence on urbanisation is mixed (Giebel et al., 2025; Mollalo et al., 2025). A recent meta-analysis found higher Alzheimer's disease dementia prevalence in rural than urban settings, particularly in lower-resource regions, while a systematic review showed that rural populations often face delayed diagnosis and reduced access to dementia care (Giebel et al., 2025; Mollalo et al., 2025). Thus, affluence and urbanisation may shape dementia burden through both underlying risk exposure and differences in healthcare access and diagnostic infrastructure.

Sex differences in dementia risk are also widely reported. Women generally experience higher dementia incidence and prevalence than men, which has been attributed to a combination of longer life expectancy, hormonal and reproductive factors, and broader sociocultural influences (Beam et al., 2018; Huque et al., 2023; You, 2025b). These established sex differences underscore the importance of examining dementia patterns separately for males and females in epidemiological research (IHME, 2023).

Despite increasing research, the global relationships among dairy supply, demographic factors, and dementia incidence remain unclear. Most studies have relied on individual-level dietary data, regional cohorts, or specific dairy products, which limits generalisability across populations. There remains a lack of population-level evidence assessing whether dairy availability contributes independently to dementia incidence when accounting for ageing, economic affluence, biological ageing burden, and urbanisation (Lee et al., 2018; Villoz et al., 2024). Therefore, this global ecological study examined whether dairy supply predicts total, male, and female dementia incidence across countries after controlling for major demographic and development-related factors at the population level.

Materials and methods

Data collection and selection

For this global ecological study, data were compiled from major international datasets maintained by United Nations bodies and the Institute for Health Metrics and Evaluation (IHME). Dementia incidence data were obtained from the IHME database (IHME, 2023), and a standardised list of 204 geographic units was sourced from the World Bank to ensure consistent alignment across variables. In this study, the term *country* refers to any territorial unit that reports its own demographic, health, and economic statistics within international reporting frameworks. As this does not necessarily imply political independence, the terms *country* and *population* are used interchangeably throughout the analysis (The World Bank, 2022a).

The main explanatory variable was dairy supply, defined as the mean per-person daily availability of dairy products between 2019 and 2021. These data were retrieved from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) Food Balance Sheets (FBS) and expressed as kilocalories per capita per day (FAO, 2025).

For each country, total dairy supply was calculated by summing the energy contributions from the FAOSTAT categories Butter and Ghee (F2740), Cream (F2743), and Milk – Excluding Butter (F2848). Category-specific values reported as *Food supply (kcal/capita/day)* were extracted for each year, averaged across 2019–2021, and combined into a single aggregated measure. This variable reflects the energy supply derived from dairy products available for human consumption at the national level. Although it does not quantify specific nutrient components and may overrepresent fat-rich products such as butter and ghee, it provides a widely used ecological indicator of population-level dairy availability and dietary exposure patterns.

FAOSTAT Food Balance Sheets were selected because this study examined dairy exposure as a population-level food availability measure rather than as individual dietary intake. Food Balance Sheets provide standardised national estimates of per-capita food and energy availability, which aligned with the ecological objective of the study and with the construction of a total dairy supply variable in kcal/capita/day. By contrast, the Global Dietary Database (GDD) primarily estimates individual intake and reports separate dairy-related variables rather than a directly comparable total dairy-energy measure, while IHME Global Burden of Disease (GBD) dietary risk estimates are designed for comparative risk assessment and include milk as a specific dietary risk rather than total dairy supply. Nevertheless, intake-based datasets such as GDD may be valuable in future studies aimed at distinguishing dairy subtypes and approximating individual-level consumption patterns.

The outcome variable was dementia incidence rate, defined as the number of new cases per 100,000 people. These data were obtained from the 2021 IHME dataset (IHME, 2023).

IHME, an independent centre based at the University of Washington, is widely recognised for its global health monitoring and analytical rigour (IHME, 2023; Murray & Frenk, 2008). Three outcome measures were extracted: overall dementia incidence, male dementia incidence, and female dementia incidence.

Because dementia arises from multiple interacting factors, several potential confounders were included. Economic affluence was measured using 2018 per-capita gross domestic product adjusted for purchasing power parity (GDP PPP) from the World Bank. Higher economic affluence is associated with greater longevity, higher education levels, and increased prevalence of lifestyle-related conditions such as obesity and diabetes (Talukdar et al., 2020; The World Bank, 2018; Xu et al., 2017). It may also affect the ability of health systems to detect dementia earlier, reflecting differences in healthcare capacity across countries (Gaziano et al., 2010). Economic affluence and urbanisation were included as key socioeconomic indicators because they may influence dementia burden through multiple pathways, including longevity, lifestyle change, healthcare access, and diagnostic capacity.

Genetic vulnerability was assessed using the Biological State Index (I_{bs}), a population-level measure intended to reflect the extent to which deleterious genetic variants may accumulate within a population. The index ranges from 0 to 1.0 and was calculated using fertility data from 2005 (WHO, 2015) and mortality data from 2009 (WHO, 2012). Its underlying premise is that reduced natural selection in modern populations may allow deleterious genetic variants to persist and accumulate, potentially contributing to population-level genetic vulnerability to non-communicable diseases such as dementia. Higher I_{bs} values therefore indicate greater population-level genetic vulnerability and have been associated with increased dementia incidence in prior ecological research (Beam et al., 2018).

Population ageing was approximated using life expectancy at birth, obtained from the World Bank (The World Bank, 2022b). Although dementia can occur at different life stages, it is concentrated primarily among older adults; therefore, life expectancy data from 2018 were used as a proxy for population ageing. While life expectancy at birth may partly reflect early-life mortality, in contemporary populations much of its variation is driven by adult and older-age survival. It remains a widely used and internationally comparable indicator of population longevity in cross-national analyses (Cambois et al., 2023; You et al., 2025).

Urbanisation, defined as the percentage of the population living in urban areas in 2018 (The World Bank, 2018), was also obtained from the World Bank. Urban settings may influence dementia risk through changes in lifestyle and health-related behaviours. Modernisation and industrialisation are associated with shifts in diet, including greater intake (You & Henneberg, 2016a; 2016b), increased consumption of processed foods high in salt, sugar, and fat (Smith et al., 2012), and generally lower levels of physical activity (Allender et al., 2008). At the same time, urban areas often provide better access to health services, which may facilitate earlier recognition and diagnosis of dementia and thereby influence reported incidence figures.

All variables were collated and managed in Microsoft Excel® 2016 prior to analysis. Within this ecological framework, each country or population was treated as one observational unit. The number of countries included in specific analyses varied across variables because complete data were not consistently available for every indicator, reflecting reporting gaps across United Nations–affiliated data sources.

Statistical analyses

The association between national dairy availability and dementia incidence (total, male, and female) was investigated through a staged analytical strategy.

1. Preliminary Data Screening: Initial visual assessments were undertaken by producing scatterplots in Microsoft Excel® 2016 to explore broad patterns between dairy supply and dementia incidence and to detect potential outliers or inconsistencies in reporting, thereby supporting data reliability.
2. Correlation Analyses: Both Spearman's rho and Pearson's r correlation coefficients were calculated to determine the magnitude and direction of relationships among dairy supply, dementia incidence indicators, economic development (GDP PPP), genetic vulnerability (I_{bs}), life expectancy (Ageing), and urbanisation. These analyses provided an overview of how dementia outcomes align with development-related variables at the global level.
3. Adjusted Correlation Models: Partial correlations were then used to examine the association between dairy supply and dementia incidence while statistically adjusting for GDP PPP, I_{bs}, Ageing, and urbanisation. This allowed assessment of whether dairy supply remained related to dementia

incidence independent of major demographic and socioeconomic influences.

4. Principal Component Analysis (PCA): To examine shared variance among key variables, PCA using Kaiser's criterion (eigenvalues ≥ 1) was conducted.
5. Regression Modelling: Regression diagnostics were used to assess multicollinearity, residual normality, and homoscedasticity using tolerance, variance inflation factors (VIF), and inspection of residual plots. Multiple linear regression analyses were then conducted to examine predictors of total, male, and female dementia incidence. Dementia incidence was specified as the dependent variable, with dairy supply and prespecified development-related indicators entered as independent variables. Enter models were treated as the primary analyses to assess the simultaneous contribution of all covariates, whereas stepwise models were used only as an exploratory model-reduction approach. Entry and removal criteria for stepwise regression were set at $p \leq 0.05$ and $p \geq 0.10$, respectively. Changes in R^2 and standardised beta coefficients were examined to assess the independent contribution of dairy supply after adjustment for demographic and socioeconomic factors. Because the primary inferential analyses were based on linear models, the polynomial trendline in Figure 1 was included for descriptive visualisation only and was not interpreted as a formal test of non-linearity.
6. Regional Stratified Analyses: To examine whether the association between dairy supply and dementia incidence varied across population contexts, correlation analyses were also conducted within selected subgroup classifications. These regional and subgroup analyses were treated as exploratory and were used to assess variation across economic, geographic, and cultural groupings. Because several subgroup sample sizes were small and multiple comparisons were performed, these findings were interpreted cautiously as hypothesis-generating rather than confirmatory. Countries were stratified according to several international frameworks, including World Bank income groups (high, upper-middle, lower-middle, and low income) (World Bank, 2022); United Nations designations of developed and developing countries (United Nations Statistics Division, 2013), WHO regional groups: Africa, the Americas, Eastern Mediterranean, Europe, South-East Asia, and the Western Pacific (WHO, 2025b), cultural, political, and economic blocs: Asia Cooperation Dialogue (Asia Cooperation Dialogue, 2018), Asia-Pacific Economic Cooperation (Asia-Pacific Economic Cooperation, 2015), the Arab World (The World Bank, 2015), English-speaking countries (official government sources), Latin America (The United Nations Educational Scientific and Cultural Organization, 2014), Latin America and the Caribbean (The United Nations Educational Scientific and Cultural Organization, 2014), OECD member states (OECD, 2015), and the Southern African Development Community (Southern African Development Community, 2015).

All statistical analyses were carried out using Statistical Package for Social Sciences version 31 (SPSS Inc., Chicago, IL, USA) alongside Microsoft Excel® 2016. A significance threshold of $p < 0.05$ was applied, with results also presented at the $p < 0.01$ and $p < 0.001$ levels where relevant.

Results

To our knowledge, this is among the first global ecological analyses to investigate whether total dairy supply predicts dementia incidence across countries. A positive association was observed, supported by correlation, regression, and partial correlation analyses, with dairy supply remaining a modest independent predictor after accounting for ageing, economic affluence, genetic burden, and urbanisation. Regional comparisons revealed marked variability, indicating that the dairy–dementia relationship is context dependent rather than universally uniform.

Visual trend analysis of dairy supply and dementia incidence

Figure 1 shows a positive association between total dairy supply and dementia incidence across countries. Visual inspection of the scatterplot suggested that higher per capita dairy availability generally corresponded with higher dementia incidence rates. A polynomial trendline was included for descriptive visualisation only and was not intended as a formal test of non-linearity. The scatterplot also suggested clustering by level of development, with many low- and middle-income countries concentrated at lower levels of both dairy supply and dementia incidence, whereas higher-income countries tended to cluster at higher levels of both variables. Overall, the visual pattern was consistent with the correlation and regression analyses, supporting a positive association between dairy supply and dementia incidence at the global level. However, the distribution of observations also suggested that this relationship may be influenced by broader development-related factors, including ageing, economic affluence, and biological ageing burden.

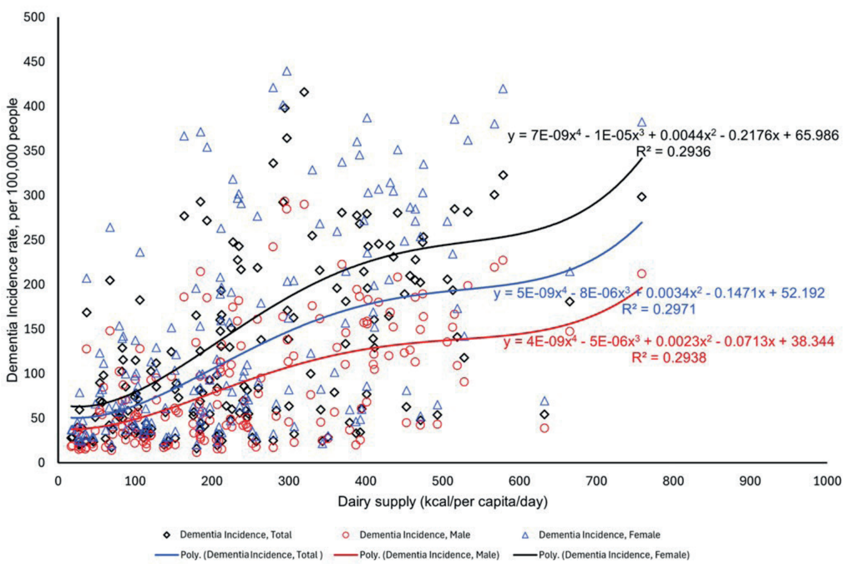

Figure 1. Scatterplot showing the association between total dairy supply and dementia incidence across countries. Note: Dairy supply (kcal/capita/day, 2019–2021) was sourced from the Food and Agriculture Organization Corporate Statistical Database, and dementia incidence (new cases per 100,000 in 2021) came from the Institute for Health Metrics and Evaluation

Global correlation patterns among dairy supply, dementia incidence, and development factors

Dairy supply was moderately and positively correlated with dementia incidence across all groups. Higher total dairy supply was associated with higher total dementia incidence (Pearson r = 0.54), as well as male and female incidence (both r = 0.53; all p <0 .001). Dairy supply was also moderately correlated with GDP per capita, I_{bs}, Ageing, and urbanisation (r range 0.45–0.53, p < 0.001), indicating that countries with greater dairy availability tended to be more affluent, more urbanised, and to have higher life expectancy.

The three dementia incidence indicators were very highly inter-correlated (r = 0.98–0.99, p < 0.001), and each showed strong positive associations with GDP, I_{bs}, ageing, and urbanisation (r generally ≥ 0.50, p < 0.001), suggesting a shared pattern across sociodemographic development and dementia burden. Spearman coefficients were very similar in magnitude to the Pearson correlations (e.g. dairy vs total dementia ρ = 0.54; dairy vs Ageing ρ = 0.55; all p < 0.001), supporting the robustness of these positive monotonic relationships and indicating that results were not driven by linearity assumptions or outliers.

Table 1. Correlation matrix of dairy supply and dementia indicators. Values in bold indicate statistical significance

Variable	1	2	3	4	5	6	7	8
1. Dairy total mean 2019–2021	1	**0.537*** **	**0.534*** **	**0.534*** **	**0.468*** **	**0.473*** **	**0.528*** **	**0.452*** **
2. Dementia incidence, total	**0.543*** **	1	**0.984*** **	**0.994*** **	**0.604*** **	**0.606*** **	**0.741*** **	**0.502*** **
3. Dementia incidence, male	**0.546*** **	**0.983*** **	1	**0.972*** **	**0.623*** **	**0.631*** **	**0.775*** **	**0.526*** **
4. Dementia incidence, female	**0.539*** **	**0.990*** **	**0.974*** **	1	**0.595*** **	**0.594*** **	**0.725*** **	**0.493*** **
5. Affluence	**0.560*** **	**0.777*** **	**0.793*** **	**0.773*** **	1	**0.567*** **	**0.733*** **	**0.649*** **
6. Genetic vulnerability	**0.597*** **	**0.848*** **	**0.870*** **	**0.844*** **	**0.895*** **	1	**0.876*** **	**0.523*** **
7. Ageing	**0.551*** **	**0.829*** **	**0.859*** **	**0.818*** **	**0.880*** **	**0.930*** **	1	**0.604*** **
8. Urbanisation	**0.459*** **	**0.525*** **	**0.549** **	**0.523*** **	**0.720*** **	**0.630*** **	**0.640*** **	1

Notes: Pearson coefficients appear above the diagonal and Spearman's rho below, with pairwise deletion applied (N = 168–204). Bolded values indicate statistically significant associations. *** p < 0.001 (2-tailed). Dairy supply (kcal/capita/day, 2019–2021) came from the Food and Agriculture Organization Corporate Statistical Database; dementia incidence (new cases per 100,000 in 2021) from the Institute for Health Metrics and Evaluation. Genetic vulnerability (I_{bs}, 2018), affluence (GDP PPP, 2018), ageing (life expectancy at birth, 2018), and urbanisation (percentage urban, 2018) were sourced from the World Bank.

Partial correlations

Partial correlations showed that the positive association between dairy supply and dementia incidence weakened after accounting for development-related factors but remained statistically significant. Controlling for affluence reduced the correlations to around .036, and further adjustment for biological state, ageing, and urbanisation lowered them to approximately 0.25–0.27 across total, male, and female outcomes. Across all models, the direction and significance of the associations were consistent, indicating that dairy supply contributes a modest independent effect beyond key socioeconomic and demographic influences. These findings highlight that broader development conditions explain much of the variation in dementia incidence, while dairy availability still plays a small but meaningful role.

Table 2. Partial correlations between dairy supply and dementia incidence under different adjustment models. Values in bold indicate statistical significance

Adjustment Model (Control Variables stabilised)	Dairy ↔ Dementia Total	Dairy ↔ Dementia Male	Dairy ↔ Dementia Female	n
Full model: Affluence + Genetic vulnerability + Ageing + Urbanisation	0.256***	0.249***	0.267***	162
Affluence + Genetic vulnerability + Ageing	0.256***	0.249***	0.265***	163
Affluence + Genetic vulnerability	0.276***	0.269***	0.284***	164
Affluence only	0.358***	0.356***	0.362***	166
Unadjusted (Pearson r)	0.537***	0.534***	0.534***	173

Notes: Partial correlation coefficients (r) are shown. *** $p < 0.001$ (2-tailed). Dairy supply (kcal/capita/day, 2019–2021) came from the Food and Agriculture Organization Corporate Statistical Database; dementia incidence (new cases per 100,000 in 2021) from the Institute for Health Metrics and Evaluation. Genetic vulnerability (I_{bs}, 2018), affluence (GDP PPP, 2018), ageing (life expectancy at birth, 2018), and urbanisation (percent urban, 2018) were sourced from the World Bank.

Principal component analysis

Principal component analysis demonstrated that the country-level variables shared a strong underlying structure. Sampling adequacy was acceptable (KMO = 0.756), and Bartlett's test indicated sufficient intercorrelations among variables ($\chi^2(10) = 512.20$, $p < 0.001$). Only one component met the Kaiser criterion (eigenvalue = 3.34), accounting for 66.7% of the total variance, suggesting a dominant latent dimension. Ageing, GDP per capita, I_{bs}, and urbanisation showed high communalities (0.58–0.85) and strong factor loadings (0.76–0.92), while dairy supply displayed a moderate loading (0.70). This pattern indicates that dairy availability is embedded within a broader cluster of socioeconomic and demographic characteristics. Overall, the extracted component appears to represent a socioeconomic–development index, reflecting shared variance among development-related indicators that co-occur with higher dairy supply across countries.

Table 3. Principal component analysis of dairy supply and country-level factors

Measure / Variable	Value / Loading	
KMO Measure of Sampling Adequacy	**0.756**	
Bartlett's Test of Sphericity	$x^2(10) = 512.20$, **p < 0.001**	
Extraction Method	Principal Component Analysis	
Number of Components Extracted	1	
Eigenvalue (Component 1)	3.34	
Variance Explained (Component 1)	**66.7%**	
Variable	Communality (Extraction)	Component Loading
Dairy supply, total	**0.489**	**0.699**
Affluence	0.703	0.839
Genetic vulnerability (I_{bs})	0.715	0.846
Ageing (Life expectancy at birth)	0.850	0.922
Urbanisation	0.579	0.761

Notes: Only one component had an eigenvalue > 1, so no rotation was applied. Dairy supply (kcal/capita/day, 2019–2021) came from the Food and Agriculture Organization Corporate Statistical Database; dementia incidence (new cases per 100,000 in 2021) from the Institute for Health Metrics and Evaluation. Genetic vulnerability (I_{bs}, 2018), affluence (GDP PPP, 2018), ageing (life expectancy at birth, 2018), and urbanisation (percent urban, 2018) were sourced from the World Bank. Bolded values indicate key PCA results and do not denote statistical significance, except for Bartlett's test p value.

Multiple linear regression analyses (enter and stepwise methods)

Regression diagnostics indicated no major violation of model assumptions. Although some covariates were moderately to strongly intercorrelated, tolerance and variance inflation factor (VIF) values remained within acceptable limits, and inspection of residual plots suggested approximate normality and homoscedasticity.

Multiple linear regression analyses showed that ageing was the strongest independent predictor of dementia incidence across all models. The full enter models were treated as the primary analyses because they retained all prespecified covariates simultaneously. In these models, ageing remained highly significant across total, male, and female dementia incidence outcomes ($\beta = 0.596$–0.754, $p < 0.001$), whereas affluence, genetic vulnerability (I_{bs}), and urbanisation were not significant independent predictors ($p > 0.05$). Adding dairy supply improved model fit across all three outcomes, increasing explained variance by approximately 2% to 4% ($\Delta R^2 = 0.022$–0.033) and reducing the standard error of the estimate. Dairy supply also remained an independent predictor of dementia incidence in the adjusted enter models (total: $\beta = 0.209$, $p < 0.001$; male: $\beta = 0.190$, $p = 0.001$; female: $\beta = 0.223$, $p < 0.001$), although its effect size was modest relative to ageing.

Table 4. Multiple linear regression models predicting dementia incidence (enter models as primary analyses; stepwise models as exploratory analyses)

Outcome & Model	R	R^2	Adj. R^2	SE	ΔR^2	Significant Predictors (β, p)	Stepwise Predictors Retained
Dementia incidence, total							
ENTER Model 1: Affluence, Genetic vulnerability, Ageing, Urbanisation	0.743	0.552	0.541	65.36	–	Ageing (**0.788, <0.001**)	Ageing
ENTER Model 2: + Dairy supply	0.761	0.579	0.566	62.09	0.027	Ageing (**0.634, <0.001**); Dairy supply (**0.209, <0.001**)	Ageing + Dairy supply
STEPWISE Model 1	0.734	0.538	0.536	64.23	–	Ageing (**0.734, <0.001**)	Ageing
STEPWISE Model 2	0.756	0.571	0.566	62.10	0.033	Ageing (**0.623, <0.001**); Dairy supply (**0.212, <0.001**)	Ageing + Dairy supply
Dementia incidence, male							
ENTER Model 1: Affluence, Genetic vulnerability, Ageing, Urbanisation	0.780	0.609	0.600	42.79	–	Ageing (**0.896, <0.001**)	Ageing
ENTER Model 2: + Dairy supply	0.794	0.631	0.620	40.92	0.022	Ageing (**0.754, <0.001**); Dairy supply (**0.190, 0.001**)	Ageing + Dairy supply
STEPWISE Model 1	0.772	0.596	0.593	42.31	–	Ageing (**0.772, <0.001**)	Ageing
STEPWISE Model 2	0.788	0.622	0.617	41.06	0.026	Ageing (**0.673, <0.001**); Dairy supply (**0.188, 0.001**)	Ageing + Dairy supply
Dementia incidence, female							
ENTER Model 1: Affluence, Genetic vulnerability, Ageing, Urbanisation	0.726	0.527	0.517	86.85	–	Ageing (**0.755, <0.001**)	Ageing
ENTER Model 2: + Dairy supply	0.748	0.560	0.546	82.03	0.033	Ageing (**0.596, <0.001**); Dairy supply (**0.223, <0.001**)	Ageing + Dairy supply
STEPWISE Model 1	0.717	0.514	0.511	85.21	–	Ageing (**0.717, <0.001**)	Ageing
STEPWISE Model 2	0.742	0.551	0.545	82.15	0.037	Ageing (**0.598, <0.001**); Dairy supply (**0.226, <0.001**)	Ageing + Dairy supply

Notes: Multiple linear regression was used. Enter models were treated as the primary analyses, whereas stepwise models were used only as an exploratory model-reduction approach. Across the enter models, ageing was the strongest independent predictor of total, male, and female dementia incidence, whereas affluence, genetic vulnerability (I_{bs}), and urbanisation were not significant independent predictors. Adding dairy supply improved model fit across all outcomes ($\Delta R^2 = 0.022–0.033$) and reduced the standard error of the estimate. In the stepwise models, ageing entered first and dairy supply entered second for all outcomes. Because all inferential models were linear, the results should be interpreted as indicating a positive adjusted linear association between dairy supply and dementia incidence. Data sources: the Food and Agriculture Organization Corporate Statistical Database (dairy supply, 2019–2021); the Institute for Health Metrics and Evaluation (dementia incidence, 2021); World Bank (GDP PPP, life expectancy at birth, urbanisation, 2018); Biological State Index (I_{bs}). Bolded values indicate statistically significant predicting effects. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Stepwise models were conducted as an exploratory model-reduction approach and produced a materially similar pattern. In each case, ageing was retained at the first step and dairy supply at the second step, with statistically significant improvements in explanatory power for total, male, and female dementia incidence. The consistency between the enter and stepwise models supports the robustness of the findings and suggests that the substantive interpretation was not dependent on the stepwise selection procedure. Because the primary inferential analyses were based on linear regression models, these findings should be interpreted as evidence of a positive adjusted linear association rather than as confirmation of non-linear or threshold effects.

Regional and economic variability in the dairy–dementia relationship

Exploratory subgroup analyses showed that the correlation between dairy supply and dementia incidence varied across global classifications. Significant positive correlations were observed in some middle- and higher-income settings and in selected regional groupings, including the Americas, Latin America, Latin America and the Caribbean, APEC, and English-speaking countries. However, no significant associations were observed in several other groups, including low-income countries, the Arab World, Eastern Mediterranean, and several European classifications. Some Asian subgroupings showed inverse or negative trends, although these findings should be interpreted cautiously given the small sample sizes in several groups and the large number of comparisons undertaken. Overall, the subgroup analyses suggest possible contextual variation in the dairy–dementia relationship, but these findings are exploratory and should be regarded as hypothesis-generating.

Discussion

This global ecological study examined whether country-level dairy supply predicts dementia incidence after accounting for major demographic and development-related factors. Overall, higher total dairy supply was associated with higher dementia incidence, although the strength of this relationship varied across regional and cultural groupings. Stronger associations were observed in the Americas, Latin America, the Caribbean, APEC, and English-speaking countries, rather than uniformly across the most affluent or highly urbanised settings. These findings both converge with and diverge from existing literature, underscoring the complexity of dairy–dementia relationships across intake levels, dairy types, and population contexts.

At the crude level, total dairy kcal supply showed moderate positive correlations with total, male, and female dementia incidence ($r \approx 0.53$–0.54). These associations remained statistically significant after adjustment for GDP PPP, Biological State Index (I_{bs}), ageing, and urbanisation, although they were attenuated (partial $r \approx 0.25$–0.27). Multiple regression models further showed that dairy supply contributed a small but independent proportion of variance in dementia incidence ($\Delta R^2 \approx 0.02$–0.04), whereas ageing remained the dominant predictor. This pattern suggests that dairy availability is part of a broader cluster of development-related exposures associated with dementia rather than a standalone causal factor (Villoz et al., 2024).

Table 5. Correlations between dairy supply and dementia incidence across global classifications (standardized N). Values in bold indicate statistical significance

Country Grouping (N)	Method	Dairy vs Total Dementia r (p)	Dairy vs Male Dementia r (p)	Dairy vs Female Dementia r (p)
World Bank Classification				
Low income (N=20)	Pearson	0.148 (0.533)	0.102 (.668)	0.189 (0.424)
	Spearman	0.024 (0.920)	–0.051 (.830)	0.096 (0.686)
Lower middle (N=48)	Pearson	0.269 (0.065)	0.334* (0.021)	0.286* (0.049)
	Spearman	0.204 (0.164)	0.280 (0.054)	0.209 (0.154)
Upper middle (N=51)	Pearson	0.381** (0.006)	0.331* (0.018)	0.359** (0.010)
	Spearman	0.385** (0.005)	0.299* (0.033)	0.357** (0.010)
High income (N=54)	Pearson	0.396** (0.003)	0.391** (0.003)	0.393** (0.003)
	Spearman	0.422*** (0.001)	0.416** (0.002)	0.399** (0.003)
United Nations Common Practice				
Developing (N=129)	Pearson	0.315*** (<0.001)	0.308*** (<.001)	0.313*** (<0.001)
	Spearman	0.311*** (<0.001)	0.317*** (<0.001)	0.305*** (<0.001)
Developed (N=44)	Pearson	0.015 (0.923)	0.055 (0.725)	–0.005 (0.975)
	Spearman	0.033 (0.831)	0.049 (0.754)	–0.017 (0.912)
World Health Organization Region				
AF (Africa, N=38)	Pearson	0.189 (0.257)	0.199 (0.230)	0.177 (0.288)
	Spearman	0.235 (0.155)	0.210 (0.206)	0.199 (0.231)
AM (Americas, N=34)	Pearson	0.660*** (<0.001)	0.618*** (<0.001)	0.670*** (<0.001)
	Spearman	0.639*** (<0.001)	0.565*** (<0.001)	0.631*** (<0.001)
EM (Eastern Mediterranean, N=19)	Pearson	–0.059 (0.809)	–0.075 (0.761)	–0.040 (0.871)
	Spearman	0.068 (0.781)	0.086 (0.726)	0.109 (0.658)
EU (WHO Europe, N=50)	Pearson	0.220 (0.125)	0.236 (0.099)	0.208 (0.146)
	Spearman	0.164 (0.254)	0.172 (0.233)	0.139 (0.337)
SEA (Southeast Asia, N=10)	Pearson	–0.477 (0.163)	–0.485 (0.155)	–0.449 (0.193)
	Spearman	–0.624 (0.054)	–0.758* (0.011)	–0.467 (0.174)

Country Grouping (N)	Method	Dairy vs Total Dementia r (p)	Dairy vs Male Dementia r (p)	Dairy vs Female Dementia r (p)
WP (Western Pacific, N=22)	Pearson	0.164 (0.465)	0.176 (0.434)	0.154 (0.493)
	Spearman	0.092 (0.684)	0.109 (0.629)	0.100 (0.658)
Cultural, Economic, and Political Regional Blocs				
ACD (Asia Cooperation Dialogue, N=27)	Pearson	–0.314 (0.110)	–0.343 (0.080)	–0.294 (0.137)
	Spearman	**–0.401* (0.038)**	**–0.445* (0.020)**	–0.372 (0.056)
APEC (Asia-Pacific Economic Cooperation, N=17)	Pearson	**0.570* (0.017)**	**0.595* (0.012)**	**0.548* (0.023)**
	Spearman	**0.490* (0.046)**	**0.525* (0.031)**	0.475 (0.054)
Arab World (N=19)	Pearson	0.020 (0.935)	0.029 (0.906)	0.023 (0.925)
	Spearman	0.091 (0.710)	0.111 (0.652)	0.091 (0.710)
EEA (European Economic Area, N=29)	Pearson	–0.036 (0.853)	–0.023 (0.907)	–0.041 (0.833)
	Spearman	–0.031 (0.873)	–0.017 (0.929)	–0.083 (0.670)
EU (European Union-27, N=27)	Pearson	–0.019 (0.924)	–0.020 (0.922)	–0.019 (0.926)
	Spearman	0.002 (0.993)	–0.034 (0.868)	–0.056 (0.781)
English, Official Language (N=49)	Pearson	**0.552*** (<0.001)**	**0.554*** (<0.001)**	**0.547*** (<0.001)**
	Spearman	**0.394** (0.005)**	**0.400** (0.004)**	**0.390** (0.006)**
LA (Latin America, N=23)	Pearson	**.647*** (<0.001)**	**0.605** (0.002)**	**0.650*** (<0.001)**
	Spearman	**0.597*** (0.003)**	**0.513* (0.012)**	**0.578** (0.004)**
LAC (Latin America and the Caribbean, N=32)	Pearson	**0.586*** (<.001)**	**0.529** (0.002)**	**0.595*** (<0.001)**
	Spearman	**0.582*** (<.001)**	**0.494** (0.004)**	**0.574*** (<0.001)**
OECD (Organisation for Economic Co-operation and Development, N=36)	Pearson	0.193 (0.259)	0.196 (0.253)	0.188 (0.273)
	Spearman	0.205 (0.231)	0.188 (0.273)	0.136 (0.428)
SADC (Southern African Development Community, N=16)	Pearson	0.245 (0.360)	0.221 (0.411)	0.254 (0.343)
	Spearman	0.**591* (0.016)**	0.485 (0.057)	**0.571* (0.021)**
SCO (Shanghai Cooperation Organization, N=26)	Pearson	0.088 (0.669)	0.074 (0.719)	0.089 (0.665)
	Spearman	0.081 (0.694)	0.115 (0.575)	0.049 (0.813)

Data sources and variable definitions: Dairy supply (kcal/capita/day, 2019–2021) was obtained from the Food and Agriculture Organization Corporate Statistical Database, and dementia incidence (new cases per 100,000 in 2021) was sourced from the Institute for Health Metrics and Evaluation. Significance level: Bolded values indicate statistically significant associations. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (2-tailed).

Although the independent contribution of dairy supply was modest, it may still matter at the population level because dietary exposures are widespread and potentially modifiable (FAO, 2025). However, its effect was small relative to ageing and should not be interpreted as a strong stand-alone clinical predictor or as a basis for individual dietary recommendations (Townsend et al., 2024). Rather, dairy supply is better understood as one contextual factor embedded within broader demographic and development-related processes.

Compared with individual-level evidence, our ecological findings appear partially discordant with studies reporting neutral or protective effects of dairy intake. The systematic review and meta-analysis cited in the Introduction reported that higher dairy consumption was associated with a lower risk of cognitive decline or dementia, although findings varied by sex, age, region, and dairy type (Villoz et al., 2024). Several cohort studies have also suggested that fermented or low-fat dairy products may benefit cognitive function, potentially through anti-inflammatory, antioxidant, and gut–brain mechanisms (Andersen & Alpass, 2024; Gao et al., 2025a; 2025b). In contrast, our country-level analysis indicated that greater total dairy supply was, on average, associated with higher dementia incidence, particularly in upper-middle and high-income settings and in regions such as the Americas, Latin America, and the Caribbean.

Several methodological and contextual factors may explain this discrepancy. First, our exposure was total dairy energy supply rather than individual intake. FAOSTAT food supply data reflect per capita availability and do not account for wastage, unequal distribution, or within-country heterogeneity (Balances, 2013). Countries with high dairy supply also tend to have older populations, stronger diagnostic systems, and more developed health services, all of which may increase recorded dementia incidence. The PCA findings, in which dairy supply loaded moderately on a single "development" component alongside affluence, ageing, I_{bs}, and urbanisation, support the view that dairy availability may partly function as a marker of broader socioeconomic and demographic transition rather than a discrete causal exposure (Abu Hatab et al., 2019; Delgado, 2003).

Interpretation of the findings must also consider dairy heterogeneity. Because total dairy supply was analysed as a single aggregated exposure, the study could not distinguish between fermented and non-fermented dairy products or between low-fat and high-fat dairy products. These subtypes may relate differently to cognitive health (Villoz et al., 2024), and the observed positive association may therefore reflect the combined influence of heterogeneous dairy exposures rather than a uniform effect of all dairy products. Fermented or lower-fat dairy products may support cognitive health through anti-inflammatory and antioxidant actions, gut–brain modulation, and bioactive compounds that benefit neuronal and vascular function (Anderson & Alpass, 2024; Gao et al., 2025a; 2025b). By contrast, high-fat dairy products may contribute to hyperinsulinemia, endothelial dysfunction, oxidative stress, and systemic inflammation, all of which are implicated in dementia pathogenesis (Ataei Kachouei et al., 2025; Ghosh et al., 2017). As total dairy supply was analysed as an ecological aggregate, the present findings likely reflect the net effect of multiple, potentially opposing, mechanisms.

Relatedly, our analysis combined butter and ghee, cream, and milk (excluding butter) into a single measure of total dairy energy consumption. This differs from many epidemiological studies that separate high-fat from low-fat dairy, or fermented from non-fermented products (Lee et al., 2018; Suzuki et al., 2024; Villoz et al., 2024). Existing evidence suggests that these subtypes may have opposing effects: fermented dairy and low-fat products may confer neuroprotective benefits, whereas high-fat dairy may contribute to vascular and metabolic pathways linked to dementia (Anderson & Alpass, 2024; Suzuki et al., 2024; Villoz et al., 2024). The positive association observed at the population level is therefore compatible with the possibility that, in countries with high dairy availability, total supply is disproportionately characterised by energy-dense, high-fat products consumed within Westernised dietary patterns rich in saturated fat, refined carbohydrates, and processed foods, which have been repeatedly linked to increased dementia risk (Ellouze et al., 2023; Li et al., 2022; Pongutta, 2025).

The regional patterns observed here are broadly consistent with the more nuanced findings of the meta-analysis (Villoz et al., 2024). We found significant positive correlations between dairy supply and dementia incidence in upper-middle- and high-income countries and in groupings such as the Americas, Latin America, Latin America and the Caribbean, APEC, and English-speaking countries. In contrast, no significant associations were observed in low-income countries, Africa, the Arab World, the Eastern Mediterranean, or European-based groups (EU, EEA, and WHO Europe), while some Asian groupings (ACD and SEA) showed inverse or negative trends. The meta-analysis similarly reported stronger inverse associations in Asian cohorts, where dairy intake is generally low to moderate, and no clear pattern in European cohorts, where intake is high (Villoz et al., 2024). Although the scatterplot suggested possible curvature, the present study did not formally test non-linear effects. Accordingly, the findings are best interpreted as indicating that the association between dairy supply and dementia incidence may vary across dietary and population contexts, rather than as evidence confirming a threshold or curvilinear relationship. This interpretation is also consistent with broader dietary literature showing that the health effects of specific foods often depend on background diet and intake range (Fabiani et al., 2023; Jacobs Jr & Steffen, 2003). In populations more closely adhering to Mediterranean or MIND dietary patterns, where dairy intake is generally modest and plant-based foods, fish, and unsaturated fats are emphasised, protective effects against cognitive decline and Alzheimer's disease have been reported consistently (Fu et al., 2022; Tse et al., 2025). Our results do not contradict such evidence; rather, they suggest that, at the macro level, high dairy supply may co-occur with departures from these protective patterns. The subgroup analyses should nevertheless be interpreted with caution. These analyses were exploratory, involved a large number of comparisons, and included several groupings with relatively small sample sizes. Accordingly, isolated significant findings, particularly inverse associations observed in some smaller Asian subgroupings, may reflect sampling instability or multiple-testing effects rather than robust underlying differences (Cuijpers et al., 2021; Wang et al., 2021). These results should therefore be regarded as hypothesis-generating and require confirmation in future studies using larger and more comparable regional datasets.

Our findings also align with broader demographic literature emphasising the dominant roles of ageing and genetic predisposition in dementia risk (Kim et al., 2009; Stocker et al., 2018; WHO, 2025a; You et al., 2022). Ageing emerged as the strongest predictor in all regression models ($\beta \approx 0.60$–0.80), exceeding the contributions of affluence, genetic vulnerability, urbanisation, and dairy supply. This is consistent with global burden evidence showing that population ageing is the primary driver of rising dementia incidence worldwide (WHO, 2025a). The Biological State Index further reflects how reduced natural selection in developed populations may permit the accumulation of deleterious alleles contributing to non-communicable diseases, including dementia (You et al., 2022). Dairy supply added a modest but statistically significant contribution on top of these factors, suggesting that diet-related exposures may modulate risk within a broader, largely non-modifiable landscape of ageing and genetic vulnerability. Although economic affluence and urbanisation were positively associated with dementia incidence in the correlation analyses, they were not retained as independent predictors in the final regression models, suggesting that their effects are largely embedded within broader demographic and development-related conditions.

Sex-specific findings were also broadly consistent with existing literature (Beam et al., 2018). Sex-specific analyses showed that the association between dairy supply and dementia incidence was similar in males and females. Higher dementia prevalence and incidence in women have been attributed to ageing, hormonal transitions, decreasing fertility, social roles, and gender equity (Han et al., 2023; You, 2025a, 2025b). More broadly, sex differences in dementia risk have been widely reported, with women generally showing higher prevalence and, in many settings, higher incidence than men (Beam et al., 2018; Huque et al., 2023). Proposed explanations include longer life expectancy, hormonal and reproductive factors, genetic susceptibility, and social determinants such as education, caregiving roles, and gender inequality (You, 2025b). Although we did not find strong evidence that dairy supply differentially affects male versus female dementia incidence at the population level, the consistently higher female rates reinforce the importance of examining dementia patterns separately for males and females and support the need for future sex-stratified individual-level studies, particularly those assessing interactions between diet, hormonal status, and genetic risk such as APOE4 (Gong et al., 2023; O'Shea et al., 2024; Valencia-Olvera et al., 2023).

Study limitations

Several limitations should be considered. First, as an ecological analysis based on country-level data, this study cannot support individual-level causal inference. The observed associations reflect population-level patterns and may not apply to individual dairy consumption or dementia risk. Residual confounding is also possible, particularly from unmeasured country-level factors such as education, healthcare access, physical activity, and other dietary components. In addition, IHME dementia incidence estimates are modelled and may be influenced by diagnostic capacity, especially in low- and middle-income countries where underdiagnosis remains common.

Second, total dairy supply was analysed as a single aggregated ecological indicator and therefore did not distinguish between fermented and non-fermented products or between low-fat and high-fat dairy. FAOSTAT Food Balance Sheets reflect food availability rather than actual intake and do not account for household wastage, unequal distribution, or within-country variation in consumption. The dairy variable should therefore be interpreted as an indicator of population-level availability rather than individual intake. Intake-based datasets such as the Global Dietary Database and IHME dietary risk estimates may be useful in future studies to examine dairy subtypes and better approximate individual-level dietary patterns.

Third, stepwise regression was used only as an exploratory model-reduction approach because it can produce unstable models and inflate Type I error; enter models were therefore treated as the primary analyses. In addition, although the scatterplot suggested possible curvature, non-linear effects were not formally modelled. The findings should therefore be interpreted as showing a positive adjusted association at the population level rather than a confirmed threshold or curvilinear relationship.

Finally, the subgroup analyses involved multiple comparisons across heterogeneous country groupings, several with small sample sizes, and should therefore be regarded as exploratory and hypothesis-generating.

Despite these limitations, this study adds an important ecological perspective to the literature on dairy and cognitive health. While cohort studies and meta-analyses often suggest possible benefits of specific dairy products or moderate intake (Camfield et al., 2011; Lee et al., 2018; Villoz et al., 2024), the present findings indicate that, at the country level, higher dairy availability tends to cluster with demographic and lifestyle conditions associated with higher dementia incidence. These results support caution in extrapolating benefits from specific dairy patterns to unqualified increases in total dairy consumption and are more consistent with broader whole-diet approaches, such as Mediterranean and MIND patterns, in which modest dairy intake is embedded within a cardiometabolically favourable dietary context (Lourida et al., 2019; Morris et al., 2015).

Conclusion

This study shows that global dairy supply is positively associated with dementia incidence, although this relationship is largely explained by broader demographic and socioeconomic development rather than dairy supply alone. The findings extend existing evidence by highlighting regional heterogeneity, variation across population contexts, and the importance of interpreting dairy within the broader context of dietary patterns and demographic transition. However, because this was an ecological study based on country-level data, the results should not be interpreted as evidence of individual-level causality and may not apply to individual dairy consumption or dementia risk. Because total dairy supply was analysed as a single aggregated exposure, the study could not distinguish potentially divergent effects of fermented versus non-fermented dairy products or low-fat versus high-fat dairy products. Future research using individual-level longitudinal data, together with more detailed assessment of dairy types, intake levels, and overall dietary patterns across regions, will be essential to clarify whether, and under what conditions, dairy consumption may contribute to dementia prevention or risk.

Contributions from individual authors

WY, MH, and SF contributed to the conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, and both the original draft preparation and review and editing of the manuscript. WY and SF were responsible for project administration and resources, while WY and MH contributed to the software.

Ethics approval

The study used only population-level data, with no ability to identify individuals, families, or communities, ensuring zero risk of re-identification. The University of Adelaide's Office of Research Ethics, Compliance, and Integrity (ORECI) determined that the project met exemption criteria and did not require formal ethics approval (Approval No. 36289).

Data availability

Details of all data sources are provided in the Materials and Methods section. The study used only publicly accessible international datasets from FAO, IHME, the World Bank, WHO/UN sources, and related public repositories. As these data are open access and contain no identifiable information, individual consent was not required, and no additional permissions were necessary.

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Conflict of interest

Co-author Maciej Henneberg is a member of the Anthropological Review editorial board. He had no involvement in the handling of this manuscript.

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Body height and mass of children and adolescents in Poland: age-specific centile distributions from the 2024–2025 nationwide survey

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Abstract

INTRODUCTION
Data on the growth and development of the young generation constitute a reliable indicator of the health and nutritional status of societies. They can be used as a tool for monitoring the social and economic situation of the population as a whole and for identifying groups at risk within it.

STUDY AIM
The aim of this paper was to present the empirical material underlying the centile estimation of body height and body mass in Polish children and adolescents, to describe the centile modelling procedure, and to report the resulting age-specific distributions of the analysed somatic traits.

MATERIALS AND METHODS
Our study has a cross-sectional design and is distinguished by both its large sample size and nationwide coverage. A total of 23,988 students were measured (11,880 boys and 12,108 girls) in 405 schools across all regions of Poland between May 2024 and June 2025. Body height and body mass were measured and analysed statistically.

RESULTS
The results for body height and body mass are presented as centile charts shown against raw-data scatterplots and supplemented with tables of centile values.

CONCLUSIONS
The results presented here may provide a basis for the development of up-to-date reference systems for basic somatic traits in school-aged children and adolescents aged 6–18 years.

KEYWORDS: growth, centiles, research methodology

Original article

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Introduction

Data on the growth and development of younger generations constitute a reliable indicator of the health and nutritional status of societies. They can be used to monitor the overall social and economic situation of the populations and to identify at-risk groups for potential interventions (WHO, 1995). Measurements of body height and body mass are among the fundamental tools used to assess physical development and nutritional status at the population level. Studies of children and adolescents aged 5–19 years from more than 190 countries showed that between 2000 and 2025, the prevalence of obesity increased from 3% to 9.4% and exceeded underweight prevalence globally except in Sub-Saharan Africa and South Asia (UNICEF, 2025). Findings from nationwide studies in Poland (Jarosz et al., 2016; Mazur, 2024) confirm these global trends. Recent international evidence also indicates unfavourable trends in excessive body mass among children and adolescents worldwide, including in Europe (NCD-RisC, 2024).

Growth and maturation parameters are widely used as indicators of intergenerational changes and of the biological effects of living conditions at the population level. Previous studies have documented long-term changes in body height, body mass, and maturation timing in children and adolescents in Poland (Gomula et al., 2021; Kułaga et al., 2011), as well as in many other European countries (Eiholzer et al., 2025; Júlíusson et al., 2013; Pop et al., 2021; Roelants et al., 2009; Saari et al., 2011) and globally, particularly in industrialized regions (Cole & Mori, 2018; NCD-RisC, 2020). More recent reports, however, suggest that the pace of these changes may differ from that observed in earlier decades (Kryst et al., 2022; Pastor-Fajardo et al., 2020; NCD-RisC, 2020). These observations support the need for updated empirical data describing the current somatic characteristics of younger populations.

The health status and physical development of children and adolescents are shaped by multiple biological, environmental, and social factors, which should be considered when interpreting population-level somatic data (Bielicki, 1986; Charzewski et al., 2003; Kozieł, Nowak-Szczepańska, & Gomuła, 2014). For this reason, nationwide empirical material collected according to a standardized protocol is of particular importance for developing up-to-date centile-based descriptions of basic somatic traits.

In many countries, measurements of basic somatic traits serve as growth references used to support the assessment of growth and developmental status in children and adolescents. These cross-sectional studies are typically updated every 10–15 years, as illustrated by research conducted in Finland (Saari et al., 2011), Norway (Júlíusson et al., 2013), Switzerland (Eiholzer et al., 2025), Romania (Pascanu et al., 2016; Pop et al., 2021), China (Li et al., 2009), and Poland (Kułaga et al., 2011; Palczewska & Niedźwiedzka, 2001). In more than 140 countries lacking up-to-date data for assessing growth in school-aged children and adolescents, WHO growth references are used (de Onis et al., 2007). In Europe, WHO growth references have been adopted in several countries, including Portugal, Albania, and Moldova. In Poland, the most recent nationwide reference studies based on a random sample of children and adolescents were conducted between 2007 and 2012 within the OLAF and OLA projects, and their findings were published as the Polish 2010 and 2012 reference systems for school-aged and preschool children, respectively (Kułaga et al., 2011; 2013; 2015).

The data analysed in the present paper were collected as part of the project "Centile Charts for Body Height, Body Weight, and Body Mass Index in Children and Adolescents in Poland", funded by the Ministry of Science and Higher Education under the Science for Society II programme. The project was designed to obtain a nationwide empirical dataset for the development of up-to-date centile distributions of basic somatic traits in school-aged children and adolescents. Field examinations were conducted in 2024–2025 in schools across all regions of Poland, using a standardized student selection procedure based on the assumptions previously applied in the OLAF project, along with a standardized anthropometric measurement protocol.

Against the background of the broader objectives of the project, the present paper focuses on a specific scope of data analysis and result presentation. The aim of this paper is to present the empirical material underlying the centile estimation of body height and body mass in Polish children and adolescents, including the relationship between the age and territorial structure of the study sample and that of the nationwide population, as well as to describe the method used to develop centile distributions and to present the results of centile modelling for the analysed somatic traits.

The results presented in this paper provide an empirical basis for further work on updated reference systems for basic somatic traits in Polish school-aged children and adolescents. Additional analyses based on the same dataset will be presented separately.

Materials and methods

The research project was reviewed by the Research Ethics Committee operating at the Institute of Sport – National Research Institute (approval No. KEBN-24-100-AP). Field examinations were conducted in 405 schools across all regions of Poland between May 2024 and June 2025. The school selection procedure was based on the sampling framework previously applied in the OLAF project (Kułaga et al., 2011), which was designed to approximate the population structure of children and adolescents in Poland. The original OLAF school list served as the starting point for sample construction in the present study, and approximately 76% of the schools included in the current survey had also participated in the OLAF project. Some schools from the original list could not be retained, mainly because of changes in the educational system following the abolition of lower secondary schools. To preserve, as far as possible, the assumptions of the original sampling framework and territorial and environmental comparability, these schools were replaced by the nearest schools enrolling students in the relevant age range.

Student selection followed a multi-stage systematic sampling procedure. At the school level, one class group from each educational level was selected. Within the selected class group, every third student was chosen from the class register, separately for girls and boys. After the candidates had been identified, written informed consent was obtained from the parents or legal guardians of minors and from students who were of legal age. In the absence of consent, the next student on the list was invited to participate, and the procedure was continued until the target number of participants had been reached or the list had been exhausted. At each educational level within a participating school, the plan was to include, within the selected class group, at least 3 students of each sex in primary schools and at least 6 students of each sex in post-primary schools, as well as 2 reserve students in each case.

The study had a cross-sectional design and was conducted in school settings according to a standardized measurement protocol. Measurements were performed by a team of 20 experienced anthropologists, each responsible for examinations in a designated region of the country. Before the start of data collection, all examiners underwent training in measurement techniques and error identification procedures.

The exact age of each participant on the day of examination was calculated as the difference between the examination date and the date of birth, expressed in days. For descriptive purposes, age was converted into decimal years (dividing the number of days by 365.25), whereas the continuous age variable used in modelling was expressed in months (age in years × 12).

Anthropometric techniques

Anthropometric measurements were performed during morning hours on a single day in each school among students selected for the study who were present on the examination day. This approach helped reduce within-day variation in the recorded values. Body height was measured in duplicate with a GPM anthropometer. Measurement error was calculated separately for each examiner. The Type A evaluation of standard uncertainty yielded values ranging from 0.01 to 0.03 cm, indicating very high repeatability of body height measurements. Participants were measured barefoot, with heels together, standing upright, shoulders and hips aligned, arms hanging freely, and the head positioned in the Frankfurt plane. Height was recorded to the nearest 0.1 cm. Body mass was measured in light underwear to the nearest 0.05 kg using a certified electronic medical scale (Charder MS6110).

Exclusion criteria

The exclusion criteria were consistent with those applied in the previous project (Kułaga et al., 2011) and included major postural abnormalities, genetic syndromes (e.g., Down syndrome, Turner syndrome), cancer, and other chronic diseases affecting growth. Additional exclusion criteria included previous growth hormone treatment or a diagnosis of growth hormone deficiency; systemic steroid therapy for conditions such as asthma or arthritis, or following renal transplantation; diabetes, cerebral palsy, cystic fibrosis, renal disease, congenital adrenal hyperplasia, congenital heart defects associated with impaired physical fitness; and thyroid hormone supplementation. Children wearing a plaster cast that could not be removed for measurement were also excluded, as its presence could affect measurement accuracy.

Statistical analysis

Body height and body mass were analysed using generalized additive models for location, scale, and shape (GAMLSS). This framework generalizes the LMS method (Cole, 1988; Cole & Green, 1992) by allowing the modelling of not only location and scale parameters but also distributional skewness (ν) and kurtosis/heavy tails (τ), which typically improves the fit to anthropometric data, particularly during puberty (Rigby & Stasinopoulos, 2005). GAMLSS-based approaches are widely used in the development of growth references and normative centile charts (e.g., Ortega et al., 2023; Tomkinson et al., 2018; WHO, 2006).

Data preparation and modelling assumptions

Data were initially recorded on paper forms and subsequently entered into a computer database (Excel). Standard quality control procedures were applied to identify and correct missing values, implausible records, duplicates, and outliers. The sample size (approximately 12,000 observations per sex, ages 6–19 years) was within the range discussed as adequate for constructing reference centiles across childhood and adolescence (Cole, 2021). Considering age expressed on a continuous scale in years, the density of observations across age supported the chosen degree of smoothing and the use of model diagnostics based on Q-tests and worm plots (Pan & Cole, 2004; Rigby & Stasinopoulos, 2005; Stasinopoulos et al., 2017).

Selection of the distribution family

To select the most appropriate distribution family, we applied a multi-stage comparative procedure based on the information criteria AIC (Akaike, 1998), BIC (Schwarz, 1978), GAIC6 and GAIC15 (Rigby & Stasinopoulos, 2005). Four distribution families commonly used in anthropometric modelling were considered: NO, BCCG, BCPE and BCT. For each outcome, five independent random subsamples comprising 33% of the dataset were drawn (subset validation). Within each subsample, we computed information-criterion deltas (ΔAIC, ΔBIC, ΔGAIC6, ΔGAIC15) as differences relative to the best model in that draw (i.e., the lowest value of a given metric) (Burnham & Anderson, 2002). The deltas were then min–max normalized within each metric and draw:

$$Norm(\Delta_j) = \frac{\Delta_j - \Delta_{min}}{\Delta_{max} - \Delta_{min}}$$

where j denotes the evaluated distribution family (NO, BCCG, BCPE, BCT).

Based on these values, a Weighted Information-Criteria Index (WICI) was computed for the BCCG, BCPE and BCT families:

$$WICI_j = 0{,}35 \times \mathrm{Norm}(\Delta AIC)_j + 0{,}35 \times \mathrm{Norm}(\Delta BIC)_j + 0{,}15 \times \mathrm{Norm}(\Delta GAIC6)_j + 0{,}15 \times \mathrm{Norm}(\Delta GAIC15)_j$$

where j denotes the evaluated family (BCCG, BCPE, BCT). WICI was restricted to BCCG/BCPE/BCT to prevent extremely large deltas for NO from dominating the min–max scaling and reducing the resolution of comparisons among shape-parameter families.

The NO family was treated as a baseline model and was allowed to be selected in each draw if it minimized the total sum of deltas ΔAIC+ΔBIC+ΔGAIC6+ΔGAIC15. In each of the five subsamples, the best family was defined as the one with the lowest WICI (or NO in the case of the baseline rule).

The final choice of distribution family followed a majority rule: we selected the family identified as best in at least three out of five draws. This threshold corresponds to the classical majority rule used in resampling procedures and reduces the impact of individual outlying draws (Efron & Tibshirani, 1993). If no family met this criterion, a fallback procedure was applied by selecting the family with the lowest mean WICI across draws. This approach was intended to ensure stability and reproducibility of the selected distribution family across the entire age range.

All analyses were performed using R (version 4.4.1; R Core Team) with the packages gamlss, gamlss.dist, and gamlss.add. The analytical workflow was implemented in custom modular R code, and reproducibility was ensured through the use of configuration files and a fixed random seed.

Full GAMLSS model estimation

Final models were fitted using GAMLSS, with the distribution family selected as described above. Age (in months) was modelled as a continuous covariate using penalized B-splines (pb) for the location parameter (μ) and, where applicable, for the scale and shape parameters (σ, ν, τ), yielding smooth age-specific trajectories in line with recommendations for modelling anthropometric traits (Cole & Green, 1992; Rigby & Stasinopoulos, 2005).

Model validation and diagnostics

Model fit was evaluated using diagnostic tools commonly recommended for GAMLSS (Rigby et al., 2019; van Buuren & Fredriks, 2001). Local diagnostics included Q-statistics and worm plots. Global diagnostics comprised residual Q–Q plots, residuals versus fitted values, residuals versus age, and residual histograms. We assessed variance stability, potential residual trends, and overall agreement between the residual distribution and the assumed theoretical model, both for the full sample and across age intervals.

Construction of centile charts

Based on the final model, the parameters μ, σ, ν and τ were predicted on an age grid with a step of 0.5 months. Selected centiles (3^{rd}, 5^{th}, 10^{th}, 15^{th}, 25^{th}, 50^{th}, 75^{th}, 85^{th}, 90^{th}, 95^{th}, and 97^{th}) were then computed as:

$$C_p = q_{Dist}(p; \mu, \sigma, \nu, \tau)$$

where q_{Dist} denotes the quantile function of the selected distribution family (e.g. qBCCG, qBCPE, qBCT). Results were stored in tabular form with columns corresponding to age, C3, C5, C10, C15, C25, C50, C75, C85, C90, C95, and C97, which served as the basis for plotting the centile curves.

Results

A total of 23,988 students were measured (11,880 boys and 12,108 girls). There were 145 children under 6 years of age (65 boys and 80 girls) and 110 participants older than 18 years (63 boys and 47 girls, respectively). The numbers of participants by age category are presented in Table 1.

Overall project coverage of the population of children and adolescents in Poland (Project/Poland; as of 31 December 2024, Statistics Poland (GUS)) within the school-age range (6–18 years) was approximately 0.45%. Excluding the boundary age groups (6 and 18 years), coverage was relatively stable and ranged from approximately 0.41% to 0.57% depending on age and sex (Table 2).

Table 1. Numbers of boys and girls in Poland by single-year age groups (as of 31 December 2024) and study participants, including population coverage (%) for each age–sex group

	Poland			Project			Project coverage (% of population)		
Years	Total	♂	♀	Total	♂	♀	%	♂	♀
5	**376235**	193241	182994	**113**	52	61	**0.03**	0.03	0.03
6	**394546**	203065	191481	**963**	477	486	**0.24**	0.23	0.25
7	**413447**	212224	201223	**1725**	862	863	**0.42**	0.41	0.43
8	**397373**	204014	193359	**1959**	965	994	**0.49**	0.47	0.51
9	**388864**	199717	189147	**1925**	958	967	**0.50**	0.48	0.51
10	**391768**	201074	190694	**2043**	984	1059	**0.52**	0.49	0.56
11	**384808**	197494	187314	**1923**	976	947	**0.50**	0.49	0.51
12	**404112**	207785	196327	**1948**	938	1010	**0.48**	0.45	0.51
13	**403700**	207601	196099	**1936**	962	974	**0.48**	0.46	0.50
14	**427402**	219643	207759	**2333**	1156	1177	**0.55**	0.53	0.57
15	**431473**	220925	210548	**2240**	1131	1109	**0.52**	0.51	0.53
16	**425435**	217734	207701	**1844**	916	928	**0.43**	0.42	0.45
17	**396544**	203123	193421	**1789**	855	934	**0.45**	0.42	0.48
18	**375848**	192539	183309	**1096**	569	527	**0.29**	0.30	0.29
19	**360994**	184567	176427	**147**	76	71	**0.04**	0.04	0.04
20	**348832**	178704	170128	**2**	1	1	**0.00**	0.00	0.00
21	**342203**	174751	167452	**2**	2	0	**0.00**	0.00	0.00
Total	**6663584**	**3418201**	**3245383**	**23988**	**11880**	**12108**	**0.36**	**0.35**	**0.37**

Categories ≥20 years were rare (n=2 each) and are shown for completeness. Totals are shown in bold.

Table 2. Comparison of participant counts by age category using age at examination and reference age (31 December 2024)

	N (exam age)			N (ref. age, 31 Dec 2024)			ΔN [1] – [2]			Δ% (vs ref.)		
	[1]			[2]			[3]			[4]		
Age	♂	♀	Total	♂	♀	Total	♂	♀	Total	♂	♀	Total
4	0	1	1	0	0	0	0	1	1	—	—	—
5	65	79	144	52	61	113	13	18	31	25.0	29.5	27.4
6	521	527	1048	477	486	963	44	41	85	9.2	8.4	8.8
7	861	844	1705	862	863	1725	-1	-19	-20	-0.1	-2.2	-1.2
8	928	1013	1941	965	994	1959	-37	19	-18	-3.8	1.9	-0.9
9	966	941	1907	958	967	1925	8	-26	-18	0.8	-2.7	-0.9
10	999	1040	2039	984	1059	2043	15	-19	-4	1.5	-1.8	-0.2

Table 2 (cont.)

	N (exam age)			N (ref. age, 31 Dec 2024)			ΔN [1] – [2]			Δ% (vs ref.)		
	[1]			[2]			[3]			[4]		
Age	♂	♀	Total	♂	♀	Total	♂	♀	Total	♂	♀	Total
11	941	998	1939	976	947	1923	-35	51	16	-3.6	5.4	0.8
12	932	960	1892	938	1010	1948	-6	-50	-56	-0.6	-5.0	-2.9
13	998	1014	2012	962	974	1936	36	40	76	3.7	4.1	3.9
14	1062	1093	2155	1156	1177	2333	-94	-84	-178	-8.1	-7.1	-7.6
15	1118	1096	2214	1131	1109	2240	-13	-13	-26	-1.1	-1.2	-1.2
16	986	954	1940	916	928	1844	70	26	96	7.6	2.8	5.2
17	851	875	1726	855	934	1789	-4	-59	-63	-0.5	-6.3	-3.5
18	589	626	1215	569	527	1096	20	99	119	3.5	18.8	10.9
19	60	47	107	76	71	147	-16	-24	-40	-21.1	-33.8	-27.2
20	2	0	2	1	1	2	1	-1	0	—	—	—
21	1	0	1	2	0	2	-1	0	-1	—	—	—
All	11880	12108	23988	11880	12108	23988	0	0	0	0.0	0.0	0.0

[1] Age at examination was calculated from the date of birth and the measurement date as the number of completed years on the examination day.

[2] Reference age as of 31 December 2024 was defined as the number of completed years on 31 December 2024 (Główny Urząd Statystyczny, n.d.). Two boys declined to provide their date of birth and were therefore excluded from this comparison.

[4] Because percentage indices are unstable for small cell counts, Δ% was not reported for categories where N (age as of 31 Dec 2024) < 30 (marked as "—").

For comparisons of the age structure of the study sample with population data from Statistics Poland (GUS), reference age was defined as the number of completed years as of 31 December 2024. In contrast, statistical analyses were based on age at examination (calculated from the date of birth and the measurement date) as a continuous variable. To assess differences arising from these two age definitions, we compared the numbers of participants by age category obtained using both methods (Table 2) and calculated the agreement between age categories, and the extent of ±1-year shifts (Table 3). The percentages for $\delta=-1$ and $\delta=+1$ describe the net balance of shifts in age-group aggregation resulting from the use of different reference points. As a summary measure, we used the difference between the proportion shifted to an older category and that shifted to a younger category, which was 1.22 percentage points in boys (17.02% − 15.80%) and 1.95 percentage points in girls (17.86% − 15.92%).

To verify the comparability of the study sample with voivodeship-level school-age populations (Table 4), we used the reference age as of 31 December 2024 and restricted analyses to ages 6–19 years, consistent with the population data range and the school-age period. Analyses of test outcomes were based on age at examination.

Table 3. Agreement between age categories using age at examination and reference age (31 December 2024)

	Boys						Girls					
	δ (age-category difference)			% of participants			δ (age-category difference)			% of participants		
Age category (exam age)	δ =-1	δ =0	δ =+1	-1	0	+1	δ =-1	δ =0	δ =+1	δ =-1	δ =0	δ =+1
4	0	0	0	0.00	0.00	0.00	1	0	0	0.01	0.00	0.00
5	29	36	0	0.24	0.30	0.00	34	45	0	0.28	0.37	0.00
6	154	351	16	1.30	2.95	0.13	157	355	15	1.30	2.93	0.12
7	195	569	97	1.64	4.79	0.82	185	562	97	1.53	4.64	0.80
8	158	631	139	1.33	5.31	1.17	206	663	144	1.70	5.48	1.19
9	182	645	139	1.53	5.43	1.17	197	598	146	1.63	4.94	1.21
10	182	662	155	1.53	5.57	1.30	179	698	163	1.48	5.76	1.35
11	165	636	140	1.39	5.35	1.18	218	616	164	1.80	5.09	1.35
12	164	610	158	1.38	5.13	1.33	173	635	152	1.43	5.24	1.26
13	185	650	163	1.56	5.47	1.37	198	659	157	1.64	5.44	1.30
14	170	744	148	1.43	6.26	1.25	183	768	142	1.51	6.34	1.17
15	123	768	227	1.04	6.46	1.91	132	753	211	1.09	6.22	1.74
16	143	650	193	1.20	5.47	1.62	140	641	173	1.16	5.29	1.43
17	143	565	143	1.20	4.76	1.20	130	590	155	1.07	4.87	1.28
18	28	414	147	0.24	3.48	1.24	29	393	204	0.24	3.25	1.68
19	0	48	12	0.00	0.40	0.10	1	42	4	0.01	0.35	0.03
20	1	1	0	0.01	0.01	0.00	0	0	0	0.00	0.00	0.00
21	0	1	0	0.00	0.01	0.00	0	0	0	0.00	0.00	0.00
Total	**2022**	**7981**	**1877**	17.02	67.18	15.80	2163	8018	1927	17.86	66.22	15.92
		11 880			100			12 108			100	

δ=age category (completed years) at examination − age category (completed years) as of 31 Dec 2024; −1: one age category younger, 0: same age category, +1: one age category older. Totals are shown in bold.

Table 4. Population counts and project coverage (%) by voivodeship for boys and girls aged 6–19 years (as of 31 December 2024)

	Poland			Project			Project coverage (% of population)		
Voivodeship	Total	♂	♀	Total	♂	♀	Total	♂	♀
Dolnośląskie	**402765**	206164	196601	**1472**	742	730	**0.37**	0.36	0.37
Kujawsko-Pomorskie	**297906**	152888	145018	**1067**	534	533	**0.36**	0.35	0.37
Lubelskie	**295784**	151172	144612	**1673**	725	948	**0.57**	0.48	0.66

Table 4 (cont.)

	Poland			Project			Project coverage (% of population)		
Voivodeship	Total	♂	♀	Total	♂	♀	Total	♂	♀
Lubuskie	**146504**	75246	71258	**543**	267	276	**0.37**	0.35	0.39
Łódzkie	**331262**	170315	160947	**1325**	653	672	**0.40**	0.38	0.42
Małopolskie	**526505**	270341	256164	**2816**	1375	1441	**0.53**	0.51	0.56
Mazowieckie	**852430**	437601	414829	**2216**	1159	1057	**0.26**	0.26	0.25
Opolskie	**126401**	64912	61489	**875**	428	447	**0.69**	0.66	0.73
Podkarpackie	**314395**	161192	153203	**1576**	800	776	**0.50**	0.50	0.51
Podlaskie	**167112**	85729	81383	**871**	459	412	**0.52**	0.54	0.51
Pomorskie	**373492**	191919	181573	**1879**	915	964	**0.50**	0.48	0.53
Śląskie	**614851**	314944	299907	**1643**	804	839	**0.27**	0.26	0.28
Świętokrzyskie	**162091**	83259	78832	**1490**	746	744	**0.92**	0.90	0.94
Warmińsko-Mazurskie	**205130**	105431	99699	**1073**	533	540	**0.52**	0.51	0.54
Wielkopolskie	**547987**	281989	265998	**2248**	1122	1126	**0.41**	0.40	0.42
Zachodnio-Pomorskie	**231699**	118403	113296	**1104**	563	541	**0.48**	0.48	0.48
Total	**5596314**	**2871505**	**2724809**	**23871**	**11825**	**12046**	**0.43**	**0.41**	**0.44**

Totals are shown in bold.

Overall, project coverage of the population of children and adolescents across voivodeships (Project/Poland) was 0.43% and was consistent across most regions (approximately 0.35–0.57%; Table 4). Higher coverage was observed in Świętokrzyskie (0.92%) and Opolskie (0.69%), whereas the lowest coverage was found in Mazowieckie (0.26%) and Śląskie (0.27%). Differences in coverage between voivodeships will be accounted for through the application of weighting factors to reduce the potential impact of unequal regional coverage on the development of reference data.

The results for body height and body mass measurements were presented as centile charts shown against raw-data scatterplots and supplemented with tables of centile values, as this form of presentation was considered more appropriate for GAMLSS modelling and better reflected the empirical distribution of the analysed somatic traits than descriptions based solely on classical descriptive statistics. Figures 1,2 and Table 5,6 present individual measurements of body height, whereas Figures 3,4 and Table 7,8 show body mass measurements for boys and girls examined in the project. The points represent raw observations, whereas the lines depict selected centile curves (P3–P97) estimated using GAMLSS models over the age range 6–18.5 years, providing a descriptive summary of the study population. Corresponding model parameter estimates and selected centile values are provided in the accompanying tables.

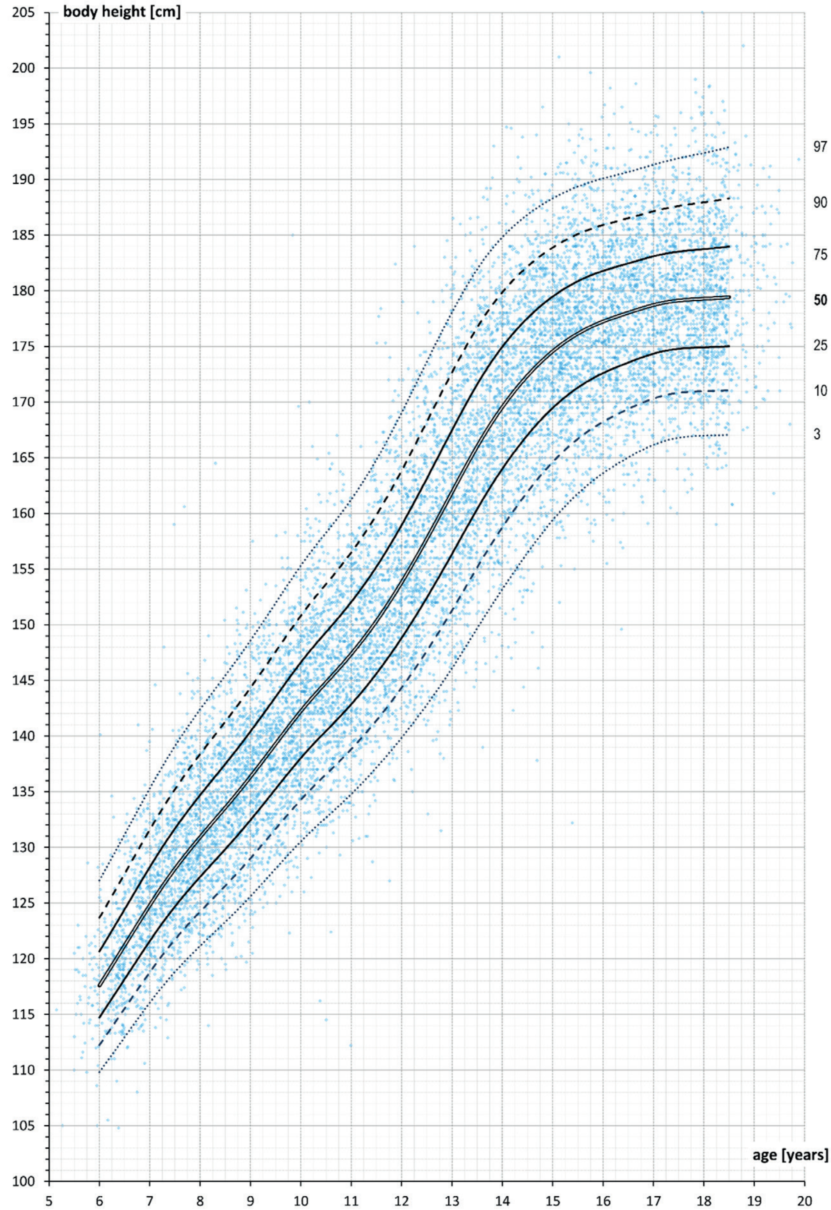

Figure 1. Body height of boys by age (5–20 years; N = 11,879) in the 2024–2025 Institute of Sport – NRI study. Points represent individual observations, and lines represent selected smoothed centile curves (P3–P97) estimated using GAMLSS. The curves were fitted only for the age range of 6.0–18.5 years, for which the number of observations was sufficient to ensure stable estimation. These curves characterize the study sample and should not be interpreted as a nationwide reference scale

Table 5. Model parameters and selected centile values for boys' body height by age

	BCT distribution				Centile values for selected age [cm]						
Age (years)	mu	sigma	nu	tau	3	10	25	**50**	75	90	97
6.0	117.59	0.037	-1.69	25.21	109.8	112.2	114.7	**117.6**	120.7	123.7	127.0
6.5	121.20	0.038	-1.51	25.21	113.0	115.5	118.2	**121.2**	124.4	127.6	131.2
7.0	124.81	0.039	-1.35	25.21	116.0	118.8	121.6	**124.8**	128.2	131.6	135.3
7.5	128.09	0.040	-1.18	25.21	118.8	121.7	124.7	**128.1**	131.7	135.2	139.1
8.0	130.93	0.041	-0.98	25.21	121.2	124.2	127.4	**130.9**	134.7	138.4	142.4
8.5	133.58	0.042	-0.75	25.21	123.3	126.6	129.9	**133.6**	137.5	141.3	145.4
9.0	136.36	0.043	-0.56	25.21	125.6	129.0	132.5	**136.4**	140.4	144.4	148.6
9.5	139.32	0.043	-0.40	25.21	128.1	131.7	135.3	**139.3**	143.5	147.6	152.0
10.0	142.25	0.044	-0.27	25.21	130.5	134.3	138.0	**142.2**	146.6	150.8	155.3
10.5	144.83	0.045	-0.16	25.21	132.7	136.6	140.5	**144.8**	149.3	153.7	158.3
11.0	147.38	0.046	-0.09	25.21	134.8	138.8	142.9	**147.4**	152.1	156.5	161.3
11.5	150.34	0.047	-0.05	25.21	137.2	141.4	145.6	**150.3**	155.2	159.9	164.8
12.0	153.81	0.048	0.07	25.21	139.9	144.3	148.8	**153.8**	159.0	163.8	169.1
12.5	157.73	0.050	0.34	25.21	142.8	147.7	152.4	**157.7**	163.1	168.2	173.6
13.0	161.91	0.050	0.76	25.21	146.1	151.3	156.4	**161.9**	167.5	172.7	178.1
13.5	166.03	0.049	1.27	25.21	149.7	155.2	160.4	**166.0**	171.6	176.7	181.9
14.0	169.57	0.047	1.75	25.21	153.2	158.8	164.0	**169.6**	175.0	179.9	184.8
14.5	172.39	0.045	2.09	25.21	156.5	161.9	167.0	**172.4**	177.6	182.2	186.8
15.0	174.57	0.042	2.19	25.21	159.4	164.6	169.5	**174.6**	179.5	183.9	188.3
15.5	176.16	0.040	2.07	25.21	161.8	166.7	171.3	**176.2**	180.9	185.1	189.4
16.0	177.25	0.038	1.78	25.21	163.6	168.2	172.6	**177.2**	181.8	185.9	190.1
16.5	178.04	0.037	1.38	25.21	165.0	169.4	173.6	**178.0**	182.5	186.5	190.7
17.0	178.72	0.036	0.94	25.21	166.2	170.3	174.4	**178.7**	183.1	187.1	191.3
17.5	179.13	0.036	0.50	25.21	166.8	170.8	174.8	**179.1**	183.5	187.6	191.9
18.0	179.29	0.036	0.11	25.21	167.0	171.0	174.9	**179.3**	183.7	187.9	192.4
18.5	179.43	0.037	-0.19	25.21	167.1	171.1	175.0	**179.4**	184.0	188.3	192.9

Values shown are model-based estimates obtained using GAMLSS under the BCT distribution. The model was fitted with age expressed in months and treated as a continuous variable. The table presents model parameter estimates and centile values for selected age points between 6.0 and 18.5 years. The symbols mu, sigma, nu and tau denote the parameters of the distribution assumed in the fitted model. Bolded values indicate the median (50th centile).

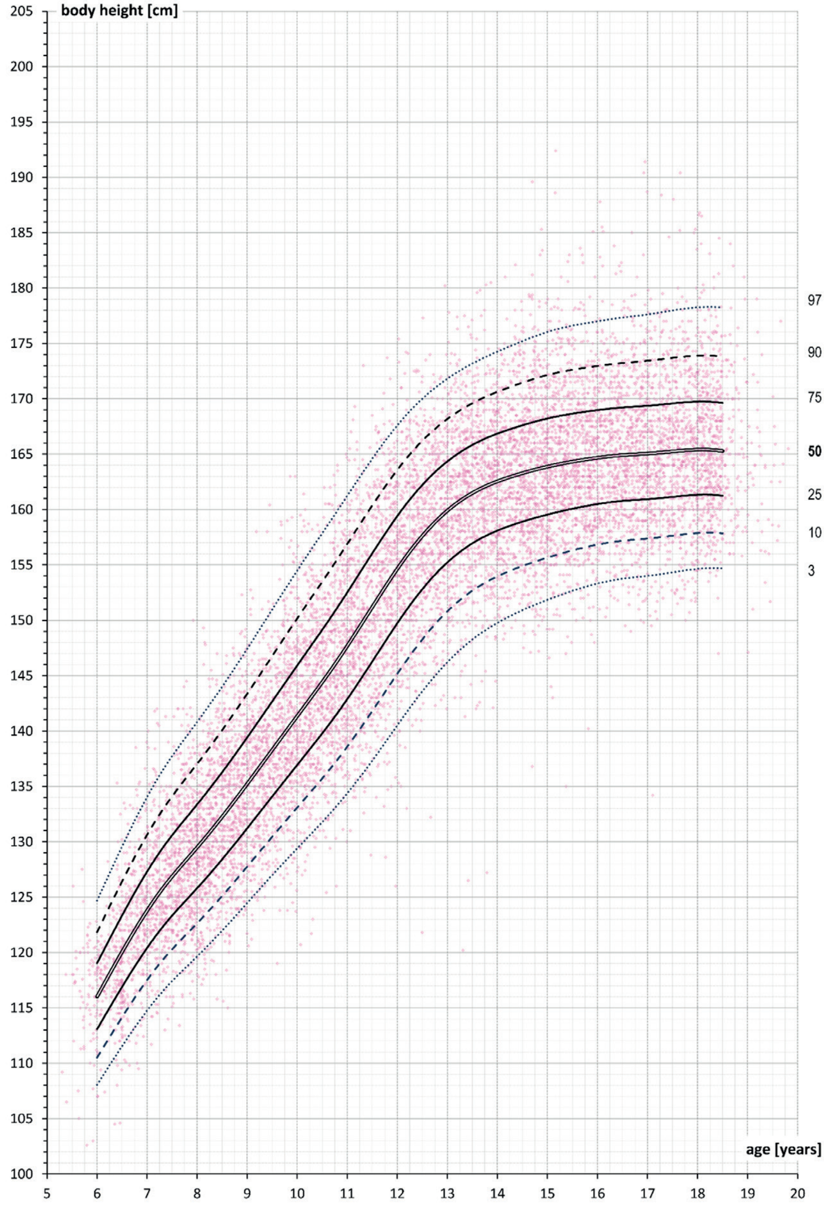

Figure 2. Body height of girls by age (5–20 years; N = 12,102) in the 2024–2025 Institute of Sport – NRI study. Points represent individual observations, and lines represent selected smoothed centile curves (P3–P97) estimated using GAMLSS. The curves were fitted only for the age range of 6.0–18.5 years, for which the number of observations was sufficient to ensure stable estimation. These curves characterize the study sample and should not be interpreted as a nationwide reference scale

Table 6. Model parameters and selected centile values for girls' body height by age

BCT distribution					Centile values for selected age [cm]						
Age (years)	mu	sigma	nu	tau	3	10	25	**50**	75	90	97
6.0	116.11	0.036	-0.30	20.19	108.1	110.5	113.1	**116.0**	119.0	121.8	124.7
6.5	120.07	0.038	-0.52	20.19	111.6	114.2	116.9	**120.1**	123.4	126.4	129.6
7.0	123.75	0.039	-0.68	20.19	114.8	117.5	120.4	**123.8**	127.3	130.6	134.1
7.5	126.84	0.040	-0.74	20.19	117.4	120.3	123.3	**126.9**	130.6	134.1	137.7
8.0	129.51	0.041	-0.69	20.19	119.7	122.6	125.8	**129.5**	133.4	137.0	140.8
8.5	132.29	0.042	-0.59	20.19	122.0	125.1	128.4	**132.3**	136.3	140.1	144.0
9.0	135.26	0.043	-0.47	20.19	124.5	127.8	131.2	**135.2**	139.4	143.4	147.4
9.5	138.30	0.044	-0.33	20.19	127.0	130.5	134.1	**138.3**	142.7	146.8	151.0
10.0	141.34	0.045	-0.10	20.19	129.4	133.1	136.9	**141.4**	145.9	150.2	154.5
10.5	144.39	0.046	0.23	20.19	131.8	135.7	139.8	**144.4**	149.1	153.5	157.9
11.0	147.65	0.046	0.65	20.19	134.4	138.6	142.9	**147.7**	152.5	156.9	161.3
11.5	151.15	0.046	1.16	20.19	137.3	141.8	146.3	**151.2**	156.1	160.4	164.6
12.0	154.59	0.044	1.67	20.19	140.5	145.2	149.7	**154.7**	159.4	163.6	167.6
12.5	157.57	0.042	2.07	20.19	143.6	148.3	152.8	**157.6**	162.2	166.2	170.0
13.0	159.86	0.040	2.24	20.19	146.2	150.8	155.2	**159.9**	164.4	168.2	171.8
13.5	161.47	0.039	2.13	20.19	148.3	152.7	157.0	**161.5**	165.8	169.6	173.2
14.0	162.52	0.038	1.75	20.19	149.8	154.0	158.1	**162.6**	166.9	170.6	174.3
14.5	163.24	0.037	1.21	20.19	150.9	154.9	158.9	**163.3**	167.6	171.5	175.2
15.0	163.81	0.037	0.66	20.19	151.8	155.7	159.5	**163.9**	168.2	172.2	176.0
15.5	164.28	0.037	0.20	20.19	152.7	156.3	160.1	**164.3**	168.7	172.6	176.6
16.0	164.66	0.036	-0.17	20.19	153.3	156.8	160.5	**164.7**	169.0	173.0	177.0
16.5	164.93	0.036	-0.46	20.19	153.8	157.2	160.8	**164.9**	169.2	173.2	177.3
17.0	165.08	0.036	-0.75	20.19	154.0	157.4	160.9	**165.1**	169.4	173.4	177.6
17.5	165.26	0.036	-1.07	20.19	154.3	157.6	161.2	**165.3**	169.6	173.7	178.0
18.0	165.39	0.036	-1.44	20.19	154.6	157.9	161.3	**165.4**	169.8	173.9	178.3
18.5	165.27	0.036	-1.82	20.19	154.7	157.9	161.3	**165.3**	169.6	173.8	178.2

Values shown are model-based estimates obtained using GAMLSS under the BCT distribution. The model was fitted with age expressed in months and treated as a continuous variable. The table presents model parameter estimates and centile values for selected age points between 6.0 and 18.5 years. The symbols mu, sigma, nu and tau denote the parameters of the distribution assumed in the fitted model. Bolded values indicate the median (50^{th} centile).

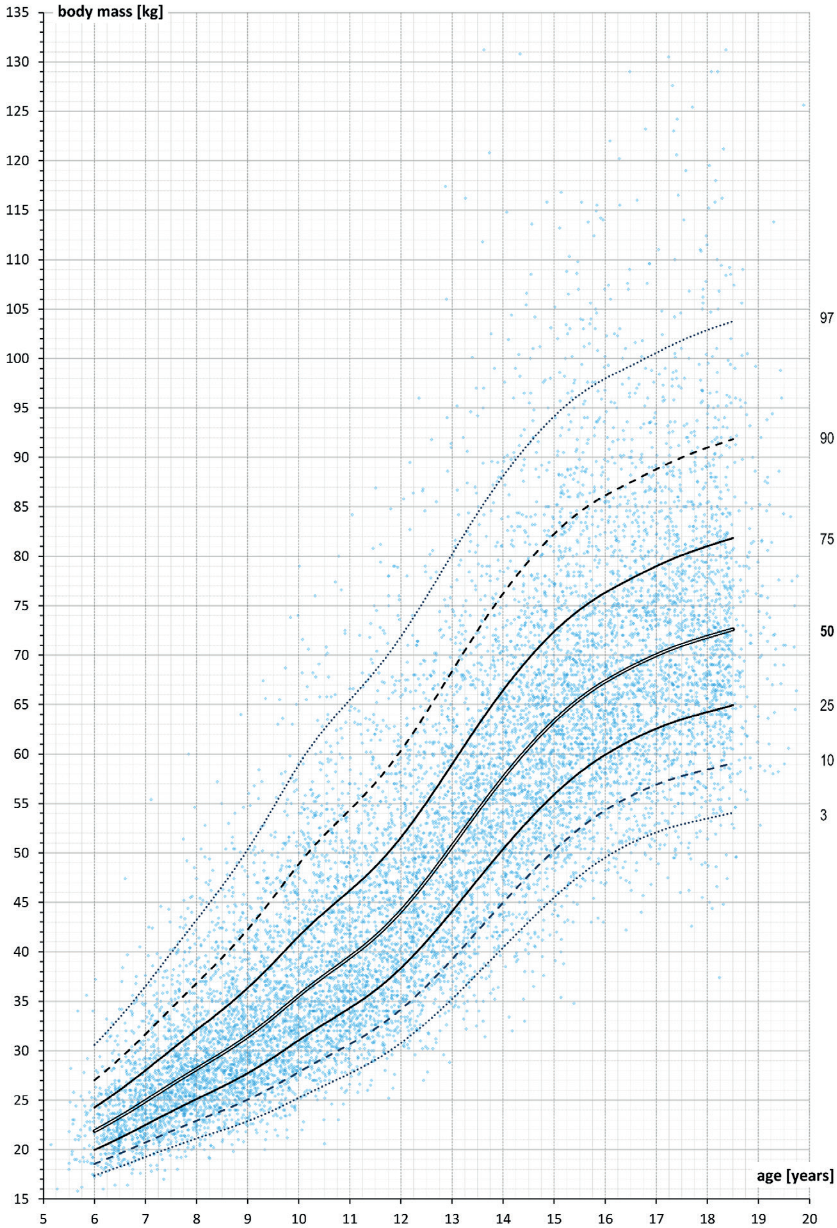

Figure 3. Body mass of boys by age (5–20 years; N = 11,879) in the 2024–2025 Institute of Sport – NRI study. Points represent individual observations, and lines represent selected smoothed centile curves (P3–P97) estimated using GAMLSS. The curves were fitted only for the age range of 6.0–18.5 years, for which the number of observations was sufficient to ensure stable estimation. These curves characterize the study sample and should not be interpreted as a nationwide reference scale

Table 7. Model parameters and selected centile values for boys' body mass by age

BCCG distribution					Centile values for selected age [kg]						
Age (years)	mu	sigma	nu	tau	3	10	25	**50**	75	90	97
6.0	21.88	0.143	-1.36	–	17.4	18.6	20.0	**21.9**	24.3	27.0	30.6
6.5	23.33	0.152	-1.31	–	18.3	19.6	21.2	**23.3**	26.1	29.2	33.4
7.0	24.93	0.162	-1.25	–	19.3	20.7	22.5	**24.9**	28.0	31.7	36.5
7.5	26.56	0.171	-1.20	–	20.2	21.9	23.8	**26.6**	30.1	34.3	39.9
8.0	28.15	0.181	-1.14	–	21.1	22.9	25.1	**28.2**	32.1	36.8	43.2
8.5	29.72	0.190	-1.07	–	22.0	23.9	26.4	**29.7**	34.1	39.4	46.6
9.0	31.45	0.200	-1.01	–	22.9	25.1	27.7	**31.5**	36.4	42.3	50.4
9.5	33.43	0.208	-0.96	–	24.0	26.4	29.3	**33.4**	38.9	45.5	54.6
10.0	35.56	0.215	-0.92	–	25.2	27.8	31.1	**35.6**	41.6	48.9	58.9
10.5	37.54	0.218	-0.89	–	26.5	29.3	32.7	**37.6**	44.0	51.8	62.5
11.0	39.43	0.219	-0.85	–	27.7	30.7	34.3	**39.5**	46.2	54.4	65.5
11.5	41.52	0.219	-0.80	–	29.1	32.2	36.1	**41.5**	48.6	57.1	68.4
12.0	44.12	0.219	-0.73	–	30.8	34.2	38.4	**44.1**	51.6	60.4	71.9
12.5	47.22	0.218	-0.65	–	32.9	36.6	41.1	**47.2**	55.1	64.2	75.9
13.0	50.67	0.215	-0.57	–	35.2	39.2	44.1	**50.7**	59.0	68.4	80.2
13.5	54.21	0.211	-0.51	–	37.8	42.1	47.3	**54.2**	62.8	72.5	84.4
14.0	57.58	0.205	-0.47	–	40.4	45.0	50.4	**57.6**	66.5	76.2	88.1
14.5	60.66	0.198	-0.46	–	43.0	47.7	53.3	**60.7**	69.7	79.5	91.4
15.0	63.35	0.191	-0.49	–	45.5	50.3	55.9	**63.4**	72.4	82.3	94.2
15.5	65.59	0.185	-0.54	–	47.7	52.5	58.1	**65.6**	74.6	84.5	96.4
16.0	67.38	0.179	-0.58	–	49.5	54.3	59.9	**67.3**	76.3	86.1	98.0
16.5	68.81	0.175	-0.61	–	51.0	55.8	61.4	**68.8**	77.7	87.5	99.3
17.0	70.04	0.172	-0.61	–	52.1	56.9	62.6	**70.0**	79.0	88.8	100.6
17.5	71.06	0.172	-0.61	–	52.9	57.8	63.5	**71.0**	80.1	90.0	101.8
18.0	71.88	0.172	-0.60	–	53.5	58.4	64.3	**71.9**	81.0	91.0	102.9
18.5	72.61	0.171	-0.59	–	54.1	59.1	64.9	**72.6**	81.8	91.8	103.8

Values shown are model-based estimates obtained using GAMLSS under the BCCG distribution. The model was fitted with age expressed in months and treated as a continuous variable. The table presents model parameter estimates and centile values for selected age points between 6.0 and 18.5 years. The symbols mu, sigma, nu and tau denote the parameters of the distribution assumed in the fitted model. Tau is not estimated for the BCCG distribution. Bolded values indicate the median (50^{th} centile).

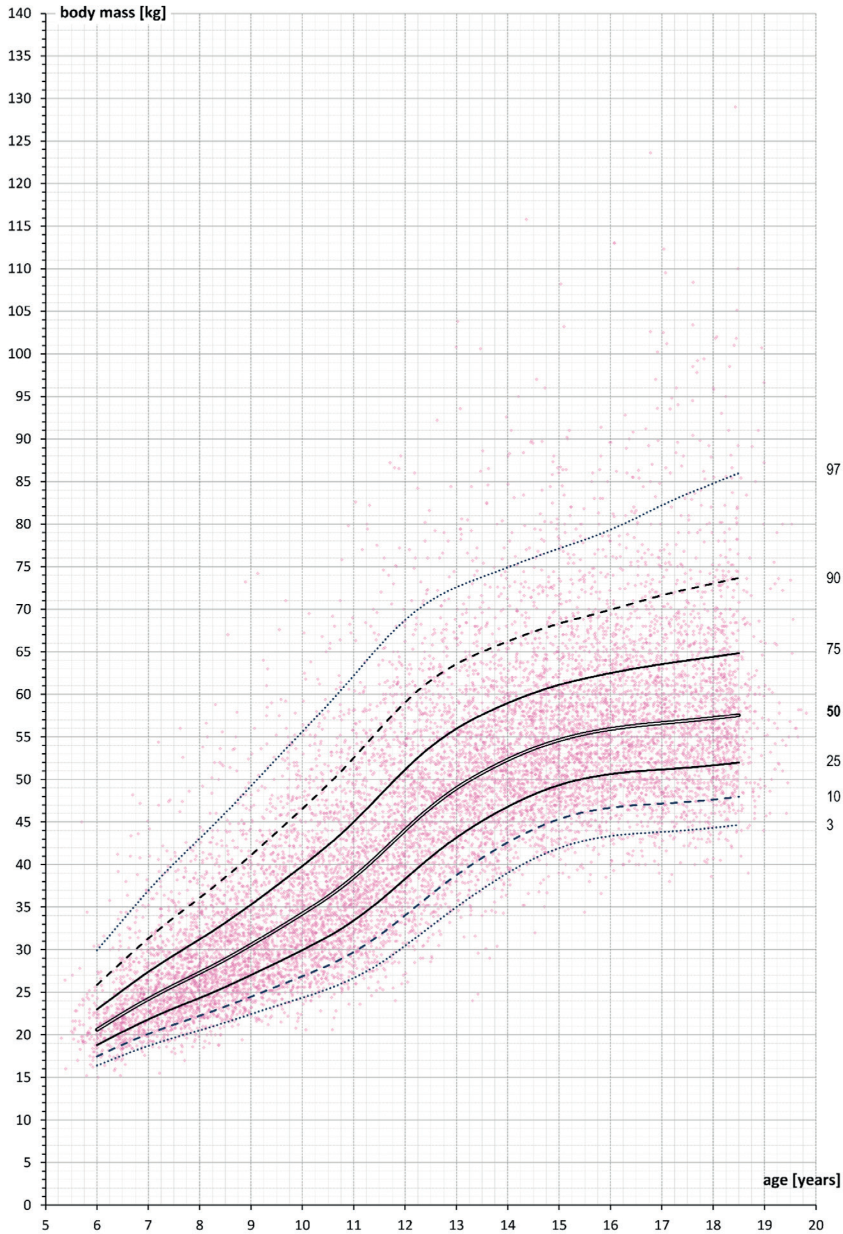

Figure 4. Body mass of girls by age (5–20 years; N = 12,102) in the 2024–2025 Institute of Sport – NRI study. Points represent individual observations, and lines represent selected smoothed centile curves (P3–P97) estimated using GAMLSS. The curves were fitted only for the age range of 6.0–18.5 years, for which the number of observations was sufficient to ensure stable estimation. These curves characterize the study sample and should not be interpreted as a nationwide reference scale

Table 8. Model parameters and selected centile values for girls' body mass by age

BCCG distribution					Centile values for selected age [kg]						
Age (years)	mu	sigma	nu	tau	3	10	25	**50**	75	90	97
6.0	20.61	0.148	-1.65	–	16.4	17.5	18.8	**20.6**	23.0	25.9	29.9
6.5	22.47	0.158	-1.57	–	17.6	18.8	20.4	**22.5**	25.2	28.7	33.5
7.0	24.22	0.167	-1.48	–	18.7	20.1	21.8	**24.2**	27.4	31.3	37.0
7.5	25.81	0.176	-1.39	–	19.7	21.2	23.1	**25.8**	29.4	33.8	40.1
8.0	27.30	0.183	-1.30	–	20.5	22.2	24.3	**27.3**	31.2	36.1	43.1
8.5	28.89	0.190	-1.21	–	21.5	23.3	25.6	**28.9**	33.2	38.5	46.1
9.0	30.60	0.197	-1.11	–	22.4	24.5	27.0	**30.6**	35.3	41.1	49.2
9.5	32.39	0.204	-1.00	–	23.4	25.7	28.5	**32.4**	37.5	43.8	52.5
10.0	34.24	0.211	-0.87	–	24.4	26.9	30.0	**34.3**	39.9	46.6	55.6
10.5	36.22	0.216	-0.75	–	25.4	28.2	31.6	**36.2**	42.3	49.4	58.8
11.0	38.52	0.220	-0.63	–	26.7	29.7	33.4	**38.5**	45.0	52.6	62.2
11.5	41.20	0.220	-0.53	–	28.4	31.7	35.7	**41.2**	48.1	55.9	65.7
12.0	44.06	0.214	-0.46	–	30.5	34.0	38.3	**44.1**	51.2	59.1	68.7
12.5	46.72	0.204	-0.43	–	32.8	36.5	40.9	**46.7**	53.8	61.6	71.0
13.0	48.96	0.192	-0.44	–	35.0	38.8	43.2	**49.0**	56.0	63.6	72.6
13.5	50.78	0.181	-0.51	–	37.1	40.8	45.1	**50.8**	57.6	65.0	73.8
14.0	52.33	0.171	-0.62	–	39.0	42.6	46.8	**52.3**	59.0	66.2	74.9
14.5	53.62	0.163	-0.76	–	40.7	44.1	48.2	**53.6**	60.2	67.3	76.1
15.0	54.64	0.158	-0.88	–	41.9	45.3	49.3	**54.6**	61.1	68.3	77.2
15.5	55.39	0.155	-0.98	–	42.8	46.2	50.1	**55.4**	61.9	69.1	78.2
16.0	55.94	0.155	-1.06	–	43.4	46.7	50.6	**55.9**	62.5	69.9	79.3
16.5	56.33	0.157	-1.14	–	43.7	47.0	51.0	**56.3**	63.1	70.8	80.7
17.0	56.63	0.159	-1.21	–	43.8	47.2	51.2	**56.6**	63.6	71.6	82.2
17.5	56.90	0.161	-1.28	–	44.0	47.4	51.4	**56.9**	64.0	72.4	83.6
18.0	57.21	0.162	-1.36	–	44.3	47.6	51.7	**57.2**	64.4	73.0	84.8
18.5	57.55	0.162	-1.44	–	44.7	48.0	52.0	**57.6**	64.8	73.7	86.0

Values shown are model-based estimates obtained using GAMLSS under the BCCG distribution. The model was fitted with age expressed in months and treated as a continuous variable. The table presents model parameter estimates and centile values for selected age points between 6.0 and 18.5 years. The symbols mu, sigma, nu and tau denote the parameters of the distribution assumed in the fitted model. Tau is not estimated for the BCCG distribution. Bolded values indicate the median (50^{th} centile).

Discussion

The tradition of research on the physical development of children and adolescents in Poland dates back to the 1930s, when the Department of Anthropology of the Central Institute of Physical Education in Warsaw conducted the first large-scale project investigating the development and physical fitness of Polish youth (Mydlarski, 1934). This line of research was continued in the 1950s, with the aim of determining the extent of deterioration in the physical development of the post-war generation of children and adolescents in Poland (Trześniowski, 1961). Subsequent nationwide representative studies on the physical development and fitness of schoolchildren were carried out in 1979 (Trześniowski, 1990), 1989 (Przewęda & Trześniowski, 1996), 1999 (Przewęda & Dobosz, 2005, 2007), and 2009 (Dobosz, 2012; Dobosz et al., 2015). At the same time, detailed somatic measurements of adults, school-aged children, and adolescents throughout the country were conducted by anthropologists from the Committee of Anthropology of the Polish Academy of Sciences in Wrocław, established to implement the Polish Anthropological Nationwide Field Investigations project. Over a period of 60 years, five editions of this project were completed (Bielecki et al., 2012; Gomula et al., 2021; Kozieł et al., 2014).

At the beginning of the present century, population reference scales for infants as well as school-aged children and adolescents in Poland were still based on studies of Warsaw populations (Palczewska & Niedźwiedzka, 2001). The most recent nationwide studies based on a random sample of children and adolescents were conducted between 2007 and 2012 within the OLAF and OLA projects, and their results were presented as the Polish 2010 and 2012 reference systems for school-aged children and adolescents and for preschool children, respectively (Kułaga et al., 2011, 2013, 2015).

The present study has a cross-sectional design and lies at the intersection of the social and medical sciences. Its particular strengths include both the large sample size and the nationwide coverage. In order to obtain a sample that reflected as closely as possible the structure of the population of children and adolescents in Poland, the study was conducted in a substantial proportion of the schools previously included in the OLAF project (Kułaga et al., 2011). The sampling methodology also drew on the assumptions adopted in the third, fourth, and fifth editions of the nationwide anthropological surveys of children and adolescents, which were carried out in the same areas of the country (Kozieł et al., 2014).

An additional strength of the data collected in the project, and a guarantee of the quality of the measurements of basic anthropometric traits, is that they were performed by a small team of 20 anthropologists experienced in conducting this type of research. The Type A standard uncertainty of measurement ranged from 0.01 to 0.03 cm. In previous nationwide studies, anthropometric measurements were performed by large teams of trained students, representatives of the medical community (Kozieł et al., 2014; Kułaga et al., 2011, 2013), or physical education teachers (Dobosz, 2012; Dobosz et al., 2015; Przewęda & Dobosz, 2005, 2007; Przewęda & Trześniowski, 1996; Trześniowski, 1961, 1990).

In the analyses of study outcomes, age at examination was used, calculated on the basis of the full date of birth and the date of measurement. In contrast, analyses of participant counts and comparisons of the sample age structure with nationwide data (Główny Urząd Statystyczny, 2025) were based on reference age, defined as completed years of age as of 31 December 2024, in accordance with the definition used in official statistics. Differences between these two age definitions were assessed on the basis of shifts in counts and flow indicators across age categories (Tables 2 and 3). In the age range of 6–19 years, these differences were small (1.22 and 1.95 percentage points) and resulted mainly from shifts between adjacent categories (±1 year), which indicates that the use of reference age does not materially distort the description of the sample age structure in population comparisons. This approach justifies relating the study results to official statistics using the age categories applied by Statistics Poland (GUS).

At the same time, the analysis of counts by age category (6–18 years) revealed both underrepresentation and overrepresentation of some age groups relative to the nationwide population. Lower relative counts were observed among boys and girls aged 6 and 18 years, whereas higher relative counts were found among 14-year-old boys and among 10- and 14-year-old girls. Even more pronounced differences concerned the territorial structure of the sample. The highest relative share of study participants was recorded in the Świętokrzyskie voivodeship (0.92%), which was approximately 3.5 times higher than the corresponding values observed in the Śląskie and Mazowieckie voivodeships. These differences do not automatically justify the conclusion that the obtained results fail to reflect the distribution of the analysed somatic traits in a large nationwide sample. They do, however, indicate the need for further analyses and the application of statistical weights to adjust the sample structure to the population structure. This step appears necessary for the development of reliable reference scales for body height and body mass in the contemporary Polish population, as well as for assessing the agreement between the unweighted characteristics presented in this paper and the estimates obtained after weighting-based correction of the sample structure.

In Poland, multiple reference systems for the assessment of physical development continue to be used in parallel, including older charts based on Warsaw data (Palczewska & Niedźwiedzka, 2001) and more recent nationwide references developed within the OLAF/OLA studies. Kułaga and Kotowska (2025) showed that the nationwide references from 2010 and 2012, developed using the LMS method accounting for distributional skewness, provide computationally consistent results near key diagnostic cut-off points, such as the 3rd centile for body height and the 95th centile for BMI, whereas older Warsaw references may lead to inconsistencies in the estimation of centiles and Z-scores.

Against this background, the approach used in our project represents a further methodological step forward. GAMLSS models generalize the LMS framework and allow the distribution family to be selected on the basis of information criteria and goodness-of-fit diagnostics, including worm plots and Q-statistics. This makes it possible to achieve a better fit of the model to the empirical shape of the distributions of somatic traits. In addition, the short period of data collection reduces the risk of within-study secular trends. The variation in cohort and voivodeship coverage identified in the present study provides a basis for the construction of weights and for adjusting the sample structure to the population structure, which will facilitate the development of updated nationwide reference data for the assessment of growth and development in school-aged children and adolescents.

It should be emphasized that the centile modelling results presented in this paper were based on a large nationwide sample; however, the analyses were performed without the application of weighting procedures correcting for differences between the structure of the study sample and that of the national population. Therefore, the resulting curves should currently be interpreted primarily as a description of the empirical distribution of the analysed somatic traits in the study sample. Although the sample size within particular age ranges was sufficient for stable modelling using the GAMLSS approach, a fuller alignment of the estimates with the structure of the nationwide population will require the application of weighting procedures in further analyses.

Conclusions

The present study, based on a cross-sectional design, is characterized by a large sample size and nationwide coverage. The high quality of the measurements of basic anthropometric traits in children and adolescents was ensured by their collection within a short period by a small team of experienced anthropologists. The methods used for data analysis are consistent with contemporary standards of statistical analysis. The results presented here provide a basis for the development of updated reference systems for basic somatic traits in school-aged children and adolescents aged 6–18 years.

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Contributions from individual authors

Anna Pastuszak and Janusz Dobosz contributed to the study conception and design. Material preparation and data collection were performed by Anna Pastuszak, Dorota Sadowska, and Janusz Dobosz. Analysis was performed by Janusz Dobosz, and Anna Pastuszak. The first draft of the manuscript was written by Anna Pastuszak, and Janusz Dobosz. Dorota Sadowska reviewed and edited the manuscript, providing revisions. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics statement

The research project was reviewed by the Research Ethics Committee operating at the Institute of Sport – National Research Institute (approval No. KEBN-24-100-AP). The reviewed materials included the study protocol, the content of the project and measurement forms, and the procedure for obtaining informed consent from respondents and their parents. Parents were asked to provide written informed consent for their child's participation in the study, whereas students expressed assent by taking part in the measurements after having been informed about the aims of the study, the confidential nature of the study and their right to withdraw at any time.

Data availability statement

Data are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that there is no conflict of interest regarding this manuscript.

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Sexual Dimorphism at Different Stages of Ontogenesis Based on the Kraków – Longitudinal Growth Study, Poland

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Abstract

Introduction and Study Aim

The aim of the study is to assess the magnitude of changes in sexual dimorphism with respect to selected morphological traits and the results of physical fitness tests between the ages of 8 and 50.

Material and Methods

The data come from the Kraków Longitudinal Growth Study and pertain to the somatic development and physical fitness of individuals born in 1970 and 1972, conducted in Kraków from 1976 and 1980 up to 2022. The Mollison Index was used to calculate sexual dimorphism.

Results

The females were shorter, lighter and thinner than the males in all analysed age groups, and differed only with regard to body height in the 13-year-olds. They were characterised by lower stronger hand strength and lower limb explosiveness throughout the analysed period. With the exception of 8-year-olds, the females had smaller arm circumference, shoulder width and thigh circumference than the males at ages 32 and 50, and at age 17, the girls demonstrated larger thigh circumference. Up until adolescence, the girls had greater body fat under the scapula, on the triceps and in the abdomen compared to the boys. However, in both 32–34- and 50-year-olds, the men exhibited greater body fat under the scapula and in the abdomen.

Conclusions

A high degree of sexual dimorphism occurs during developmental age – at the end of the adolescence period, especially for fat folds on the triceps and abdomen. Greater dimorphism is observed later, in early adulthood, i.e., at the age of 32–34 years, in terms of height and body weight, as well as body mass index,

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circumferences – of the arm and thigh, shoulder width, and performance test results. In adulthood (around the age of 50), a noticeable decrease in the degree of sexual dimorphism is observed, which results from the nature of involutional changes.

KEYWORDS: morphological characteristics, physical fitness tests results, longitudinal study, childhood, adolescence, adulthood

Introduction

Dimorphism in humans, as established in the 1950s, is based on genetic determinism of development. Biologically, an individual's masculinity or femininity is established on the basis of XX chromosomes in females and XY chromosomes in males. The resulting different ratios between androgens and oestrogens secreted by both sexes determine the course of prenatal and postnatal development, leading to biological male and female development. It is worth noting that humans, compared to the majority of primates, exhibit slight dimorphism, but it is nevertheless visible from birth (Greil, 2006). Human sexual dimorphism relates to body structure, biochemical and physiological properties, neurohormonal activity, as well as behavior patterns and lifestyle.

During prenatal life and early childhood, body composition variation is small. Immediately after birth, morphological dimorphism is primarily expressed by shorter length and birth weight, and greater body fat in girls than in boys (Greil, 2006). Developmental differences related to sex during this period are estimated to be only 2–3% (Perenc & Radochońska, 2012). During childhood, on average up to 6 years of age, sexual dimorphism remains slight, and its intensity is observed at the onset of puberty (Wells, 2007). The sexual dimorphism that intensifies during puberty is mainly the result of different developmental rates (growth and maturation) in both sexes. On average, girls develop earlier than boys, therefore, between the ages of 9 and 14, they become significantly taller and heavier. After the pubertal growth spurt (at approximately age 14), girls' development slows down, while remaining rapid for their peers. This is due to the fact that the pubertal growth spurt begins later and lasts longer in boys than in girls. This different pace of development leads to the typical morphological differences between adults of the opposite sexes developing during this period – males become taller and heavier than females (Greil, 2006). Differences in body proportions also develop during this period – girls are taller than boys and begin to have a relatively wider pelvis. Boys, on the other hand, begin to have relatively longer lower limbs and comparatively wider shoulders than their peers. Differences in body composition also emerge during this period. Girls experience an increase body fat, while boys demonstrate an increase in lean body mass – particularly muscle and bone mass (Wells 2007; Sterkowicz & Żak, 2010). A consequence of these morphological variances are sex differences related to the physiology of movement. Females have a higher heart rate, lower stroke volume, cardiac output, haemoglobin, red blood cell counts, maximal oxygen uptake and vital lung capacity (Sterkowicz & Żak, 2010). At the end of puberty and the onset of young adulthood, dimorphism becomes most apparent and is estimated at approximately 8% (Greil, 2006; Perenc & Radochońska, 2012). After late adulthood, women experience apparent biological masculinisation and oestrogen dominance appears in men (Wolański, 2006). However, this does not eliminate dimorphism, but rather changes it. According to some researchers, dimorphism decreases in old age (Wells, 2007), while others believe it increases (Wolański, 2006). The ambiguous results of research on changes in body dimorphism with age may be related to the fact that they were obtained based on cross-sectional studies (Hägg & Jylhäva, 2021; Xiao et al., 2020). However, little is known about changes in dimorphism within populations throughout their lifetime.

The population of Kraków undergoes regular monitoring of parameters related to body size, proportions, and physical fitness (Chrzanowska et al., 1988; 2002; Gołąb et al., 2003; Jasicki, 1938; 1948; Kowal et al., 2011; 2013; Kryst et al., 2023; Woronkowicz et al., 2012; Żegleń et al., 2020 and others). These were mostly cross-sectional studies.

Conducted since the 1976s and 1980s by the Department of Anthropology at the Institute of Biomedical Sciences of the University School of Physical Education, two series of continuous studies, which were merged in 2004 as the Kraków Longitudinal Growth Study (KLGS), have enabled the analysis of numerous issues, including ontogenetic changes and sexual dimorphism in the distribution of subcutaneous fat a 12-year longitudinal study of children and adolescents from Kraków (Chrzanowska & Suder, 2008); predicting the timing of reaching maturity and peak height velocity (Malina et al., 2021); age at pubarche and the risk of developing cardiometabolic complications among men aged 50–52 from KLGS (Spring et al., 2024); predicting adult height in boys: the Zarow method and a comparative analysis of different methods (Żarów, 2001); body build and physical activity in adults and it's biological development in childhood youthfulness (Żarów et al., 2006) childhood and adolescence changes in physical fitness and body composition of women and men examined in 2004 and 2022 – a longitudinal study (Żarów et al., 2024) and many other research problems.

The aim of this article is to assess the magnitude of changes in sexual dimorphism in certain morphological traits and physical fitness test results from ages 8 to 50, using the example of the KLGS. The following research question was formulated: How does the course and magnitude of changes in sexual dimorphism in ontogeny (at ages 8–50) in terms of selected morphological traits and tests of static and explosive strength of the upper and lower limbs, considered indicators of human health condition? The presented analysis of the results is primarily descriptive and partially explanatory.

Material and methods

Approval was for this research was obtained from the Bioethics Committee at the District Medical Chamber in Kraków for the study in 2022 (Consent No. 65/KBL/OIL dated April 11, 2022). The research material consists of data from KLGS on the somatic development and physical fitness of people born in 1970 and 1972, conducted in Kraków in the years 1976–2022 (KLGS 1976–2022) by research teams of the Department of Anthropology, Institute of Biomedical Sciences at the University School of Physical Education in Kraków (currently the University of Physical Culture):

- 1st series of annual examinations in the years 1976–1988 (age 6–18);
- 2nd series of annual examinations in 1980–1990 (age 8–18);

The first series of studies concerned people born in 1970; at the age of 6 there were 485 boys and 455 girls, and by the age of 18, 180 boys and 145 girls remained. The second series of studies involved people born in 1972, and at the age of 8 there were 460 boys and 360 girls, and by the age of 18, 178 boys and 108 girls remained. The decrease in the number of participants in subsequent years is a natural consequence of longitudinal studies:

- two combined series of women and men examined in 2004 (age 32–34);
- re-examination, after 18 years, of the same women and men in 2022 (age 50–52).

In total, 103 females and 122 males participated in the study in 2004, and in 2022, 47 and 67, respectively. Of these participants, 35 females and 47 males were present for both measurements in 2004 and 2022. No morphological selection of the women or men who participated in the 2022 study was observed in comparison to the 2004 trial, as the height of 103 females examined in 2004 was 165.2 cm, and 37 examinees were 164.4 cm tall; and, respectively, 178.1 cm for 122 males and 178.3 cm for 53. In terms of body mass, the values were 59.8 kg and 58.5 kg for the females, and 80.7 kg and 79.6 kg for the males.

The study included data (Table 1) on the morphological characteristics of 83 females and 92 males aged 8 to 17 and 67 and 70 for physical fitness tests. Fewer boys and girls participated in the physical fitness tests due to the inability to perform a given test on the day of the examination for various reasons (e.g., temporary injury). And in the studies conducted in 2004 and 2022, 35 females and 49 males participated. No exclusion criteria were applied in subsequent years of the study. Spontaneous selection occurred – e.g., absence on the day of the study for various reasons, change of residence, not accepting the invitation to participate in the study despite multiple email, phone, and mail invitations, deaths, etc. All participants were residents of the city of Kraków. The studied sample represented the average population of the city of Kraków.

Table 1. The number of subjects included in our study (KLGS 1976–2022).

Age (in years)	Morphological characteristics		Physical fitness tests results	
	Females	Males	Females	Males
8*	83	92	67	70
13*	83	92	67	70
17*	83	92	67	70
32–34	35	47	35	47
50–52	35	47	35	47

*Age was calculated according to the following rule: for example, eight-year-olds were considered to be people aged from 7.50 to 8.49 years, and similarly for the categories of 13- and 17-year-olds.

The following measurements were performed. Physical fitness tests included handgrip strength of stronger hand in both the right and left hand, and standing broad jump. Physical fitness tests were conducted according to the instructions of the ICSPFT test (Larson, 1974). Anthropometric measurements included:

- body height – measured according to Martin's technique using an anthropometer (GPM, Switzerland, to the nearest 1 mm);
- body mass – using an electronic scale, and since 1994 using a body composition analyser, Tanita TBF-300 (Japan), to the nearest 0.01 kg;

- thigh and mid-upper-arm (MUAC, in relaxation) circumferences measured with a non-stretchable anthropometric tape;
- of triceps, subscapular and abdominal skinfold thickness – measured with a skinfold caliper (Harpenden type with constant pressure of 10g/mm^2, to the nearest 1 mm)
- shoulder width – measured with a large spreading calliper (GPM, Switzerland, to the nearest 1 mm).

Body mass index (BMI) was calculated as the proportion of body mass in kilogrammes to body height expressed in metres squared. The level of sexual dimorphism was calculated via Mollison's Index (MI): MI = (Xf-Xm)/SDm (Drozdowski, 1998), where: Xf mean value of the parameter for females, Xm mean value of the parameter for males, SDm standard deviation of the parameter for males. Negative values of the index indicate a lower level of development of a given trait in women.

Basic descriptive statistics (means and measures of variability) were calculated. The statistical significance of the differences between the analysed sexes was estimated using the Student's t-test for independent samples. For variables where the assumption of homogeneity of variances was found to be violated – as verified using Levene's test – the Welch-corrected Student's t-test was used, which accounts for unequal variances. The calculations were performed using the Statistica 13.0 package.

Results

Table 2 shows the arithmetic means and standard deviations, which were the basis for calculating MI. The degree of sexual dimorphism according to MI of selected somatic features and physical fitness tests is presented in Figures 1–3.

Table 2. Characteristics of body features and motor skills at various stages of ontogeny of the KLGS 1976–2022 study.

	Girls N = 83; Boys N = 92			Women N = 35; Men N = 47	
	8 yrs.	13 yrs.	17 yrs.	32–34 yrs.	50–52 yrs.
	Mean; SD	Mean; SD	Mean; SD	Mean; SD	Mean; SD
Body height [cm]					
Women	127.0; 5.6	156.0; 7.2	163.7; 6.0	164.4; 5.9	164.2; 5.9
Men	127.4; 5.3	155.8; 8.4	175.0; 6.5*	178.3; 5.8*	178.0; 5.9*
Body mass [kg]					
Women	25.3; 4.3	44.2; 7.7	55.1; 6.4	58.5; 7.2	66.4; 10.9
Men	26.1; 3.8	44.7; 8.7	64.7; 7.8*	79.6; 10.7*	88.1; 16.0*
Body Mass Index [kg/m^2]					
Women	15.6; 1.9	18.1; 2.2	20.6; 2.0	21.6; 2.5	24.6; 3.9
Men	15.9; 1.7	18.3; 2.3	21.1; 2.0	25.0; 2.9*	27.8; 4.6*
Stronger hand grip strength [kG]					
Women	10.9; 3.0	23.3; 4.5	30.9; 6.0	37.4; 3.9	34.4; 4.5
Men	13.1; 4.0*	28.2; 6.7*	50.1; 9.0*	60.2; 6.9*	55.9; 7.4*

Table 2 (cont.)

	Girls N = 83; Boys N = 92			Women N = 35; Men N = 47	
	8 yrs.	13 yrs.	17 yrs.	32–34 yrs.	50–52 yrs.
	Mean; SD	Mean; SD	Mean; SD	Mean; SD	Mean; SD
			Standing broad jump [cm]		
Women	121.3; 17.4	161.8; 17.1	173.3; 17.3	163.9; 19.3	140.8; 19.8
Men	125.9; 17.3	177.5; 20.9*	218.4; 20.9*	212.2; 24.4*	182.1; 19.5*
			Arm circumference [cm]		
Women	18.5; 1.7	22.1; 2.3	25.2; 1.8	26.3; 2.3	28.5; 3.1
Men	18.4; 1.7	22.4; 2.4	27.4; 2.2*	31.0; 2.5*	32.4; 3.7*
			Thigh circumference [cm]		
Women	38.4; 3.8	48.1; 4.5	54.0; 3.6	53.0; 3.7	55.8; 5.1
Men	37.6; 3.7	46.2; 4.6*	53.2; 3.8	56.9; 4.2*	57.0; 5.3
			Biacromial diameter [cm]		
Women	27.4; 1.4	32.8; 1.7	35.3; 1.4	35.8; 1.3	36.3; 1.8
Men	27.9; 1.3*	33.2; 2.2	39.3; 2.1*	40.9; 1.6*	41.5; 1.7*
			Triceps skinfold [mm]		
Women	10.1; 3.5	11.5; 3.9	14.0; 4.1	13.7; 5.0	18.3; 5.4
Men	8.3; 2.4*	9.2; 3.1*	7.5; 2.3*	9.0; 3.3*	12.2; 5.4*
			Subscapular skinfold [mm]		
Women	7.4; 3.8	9.1; 3.7	12.1; 4.5	13.7; 6.2	19.8; 7.1
Men	5.9; 2.2*	7.3; 3.1*	8.5; 2.4*	15.3; 6.2	20.6; 7.0
			Abdominal skinfold [mm]		
Women	8.5; 5.4	10.3; 5.5	15.1; 5.5	13.2; 6.6	20.1; 6.5
Men	6.9; 3.7*	8.0; 4.8*	8.6; 3.6*	17.0; 7.5*	21.7 7.8

* statistically significant differences (p<0.05) between 8, 13 and 17-year-old boys and girls

Sexual dimorphism in body height, mass and BMI, as well as two physical fitness tests results, for individuals aged 8, 13, 17, 32–34 (2004 series) and 50–52 (2022 series) are presented in Figure 1. We considered that the age of 8 years is a good moment to indicate the pre-pubertal period for both boys and girls, 13 years old is the period of adolescence, and 17 years old is practically the end of the pubertal period. The developmental status of children aged 6 and 7 was not included in this study (Gołąb et al., 1993).

The results obtained for the females were normalised to the arithmetic mean and standard deviation of the males. Data analysis revealed that the females were shorter, lighter and slimmer compared to the males in all of the analysed age groups. The exception was height among the 13-year-olds, when girls were slightly taller than boys. The smallest differences between the sexes for all analysed traits were found at age 13, at 0.02, 0.05 and 0.07 standard deviations, respectively. In subsequent years, the level of sexual dimorphism increased until age 32–34, while at age 50–52, it decreased for all the traits under analysis.

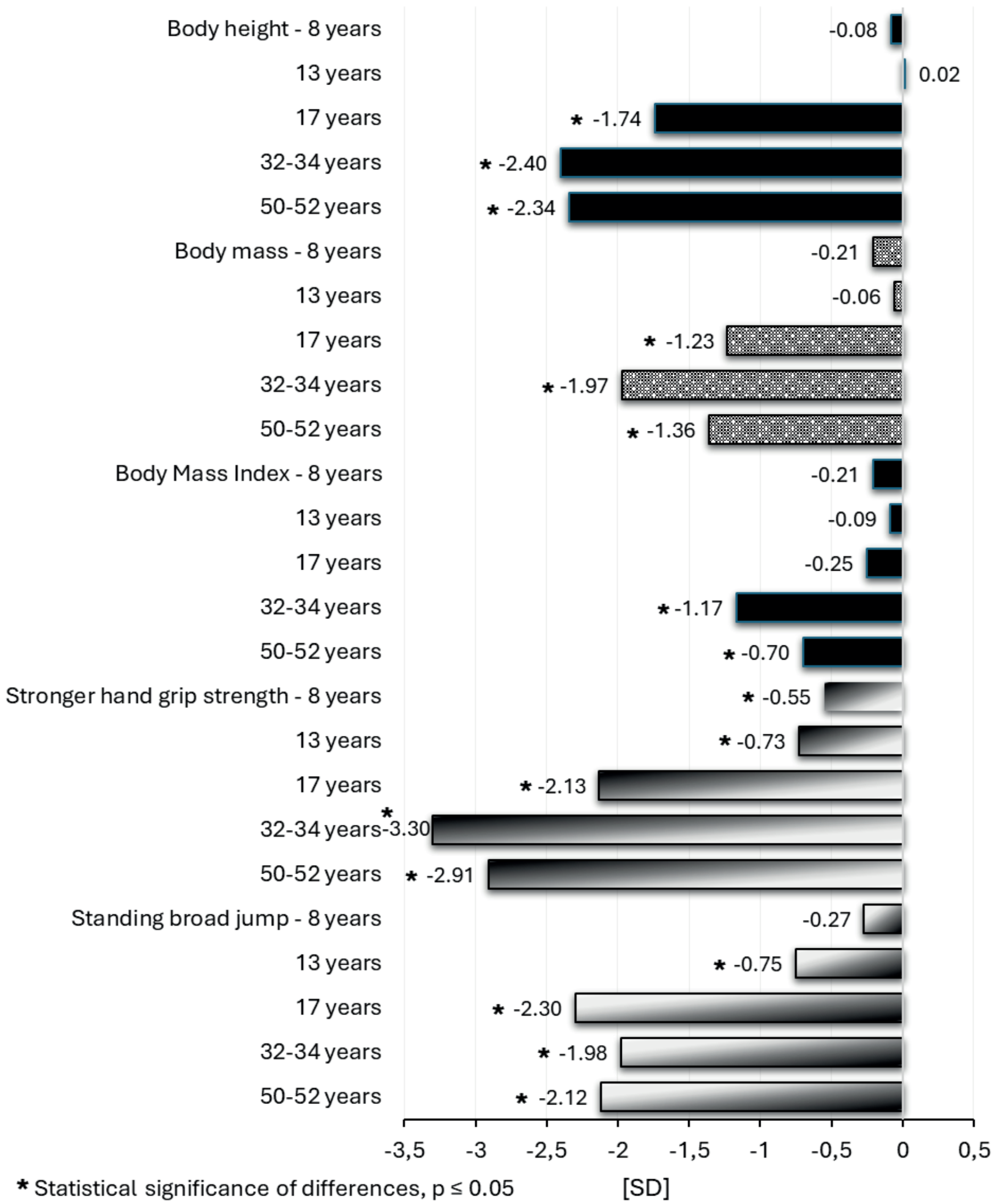

Figure 1. Mollison's Index results for height, body mass and BMI, as well as strength of stronger hand and standing long jump at ages 8, 13, 17, 32–34 and 50–52 part of the Kraków Longitudinal Growth Study.

Statistically significant differences between the sexes were found for body mass and height in the 17-year-old groups and for all analysed characteristics in the 32–34- and 50–52-year-old groups ($p<0.001$). Based on the results of physical fitness tests, it was found that throughout the analysed period, the females were characterised by lower strength in the stronger arm and lower explosive strength in the lower limbs. The level of dimorphism in explosive strength of the lower limbs increased throughout the analysed period, reaching its highest value in the 50-year-old group (2.67 standard deviations). However, the level of dimorphism in arm strength increased until the age of 32–34 and then began to decline. Statistically significant differences between the sexes were found for both characteristics in all age groups ($p<0.001$). The exception was explosive strength of the lower limbs in the 8-year-old group.

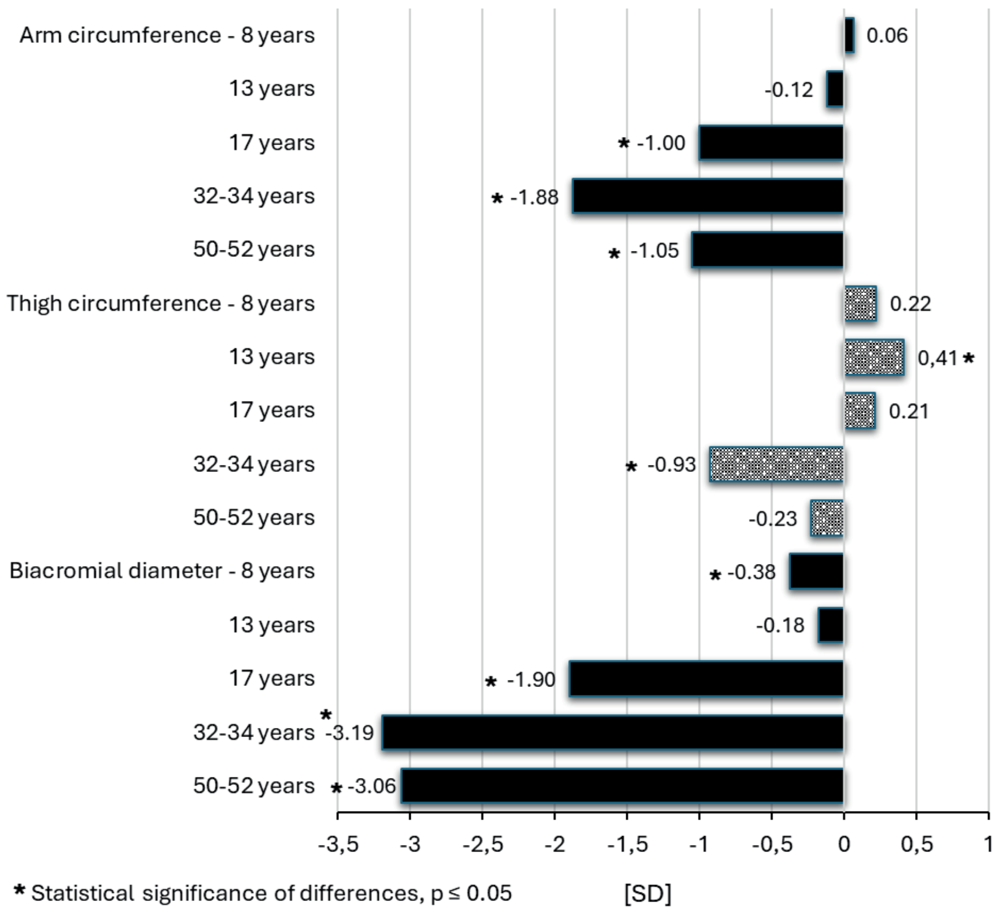

Figure 2. Mollison's Index results for arm and thigh circumference as well as biacromial diameter at ages 8, 13, 17, 32–34 and 50–52 part of the Kraków Longitudinal Growth Study.

It was found that throughout the analysed period, with the exception of 8-year-olds, the females had smaller upper arm circumferences than the males (Fig. 2). The level of dimorphism was lowest in the youngest age group, reaching 0.06 standard deviations. In subsequent years, the level of dimorphism increased, reaching a maximum value of 1.88 standard deviations in 32- to 34-year-olds, after which it decreased to 1.03 standard deviations. Differences between the sexes were statistically significant ($p<0.001$), except for the 8- and 13-year-olds. Based on the results, it was found that until the age of 17, the girls had larger thigh circumferences. The level of dimorphism in this trait was small, with statistically significant differences found only in the 13-year-olds ($p<0.01$). With age, the males began to dominate in this trait and the level of dimorphism increased statistically significantly among 32–34-year-olds ($p<0.001$), and then slightly decreased.

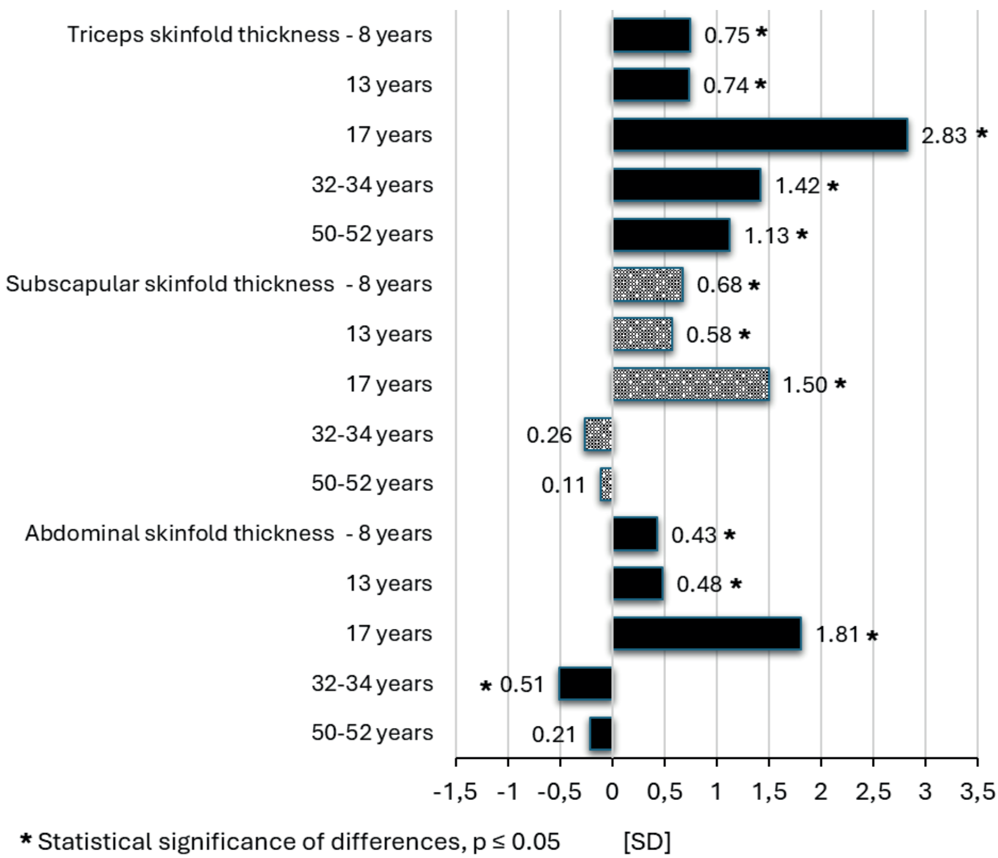

Figure 3. Mollison's Index results for body fatness at ages 8, 13, 17, 32–34 and 50–52 part of the Kraków Longitudinal Growth Study.

It was demonstrated that throughout the analysed period, the females had smaller shoulder widths than the males. The level of dimorphism in this trait during childhood was low, reaching its lowest value in the 8-year-olds. In subsequent years, the level of dimorphism in this trait increased, reaching its highest values at ages 32–34, before decreasing slightly. Statistically significant differences were found in all age groups except for the 13-year-olds.

Analysing differences in body fat levels and fat distribution (Fig. 3) revealed that until adolescence, the girls demonstrated greater body fat than the boys in the subscapular, triceps and abdominal regions. In 8-year-olds, the level of dimorphism was 0.68, 0.74 and 0.43 for standard deviations, respectively, and the differences between the sexes were statistically significant ($p<0.05$). In 13-year-olds, the level of dimorphism remained similar, but in adolescence, it reached the highest values of 0.9, 2.82 and 1.82 for standard deviations, respectively. The differences were statistically significant ($p<0.001$). In adults, the level of dimorphism decreased, reaching the lowest values in the latter age group. Importantly, both in the 32–34- and 50-year-olds, the men had higher levels of subscapular and abdominal fat. Statistically significant differences were found in triceps ($p<0.001$) and abdominal skinfold thicknesses ($p<0.05$) in the age range of 32–34, whereas in 50-year-olds, these variations were only noted in triceps skinfold thickness ($p<0.001$).

Discussion

Analysis of the results from our longitudinal research on body height and mass revealed that the females were, on average, lighter, shorter (with the exception of the average height of girls at age 13) and slimmer than the males throughout almost the entire ontogenetic period under review. However, the level of dimorphism in these traits during childhood and the onset of puberty was not statistically significant. Among 17-year-olds (the stage of puberty completion), sex differences in body mass, height and BMI became statistically significant and increased up until the age of 32–34, when they were most pronounced. They then decreased slightly after the next two decades, at the age of 52.

It is well known that at birth, boys are approximately 1 cm (approx. 1–2%) longer and slightly heavier than girls (Wells, 2007). During childhood, dimorphism of body height and mass remain slight until the onset of puberty. Therefore, girls are shorter than boys until about 9 years of age, and then, during the pubertal period—between 9 and 12 years of age—they begin to exceed their peers by approximately 0.1%–0.6%. This is due to the earlier onset of the pubertal growth spurt in boys. The height advantage in boys, leading to a more pronounced lead in this trait in adulthood, begins at 0.4% after age 13 and becomes more marked with each subsequent year. It is most noticeable in early adulthood (19–30 years), when women are 7.4%–7.6% shorter than men of the same chronological age. This height difference decreases once more in later adulthood. By age 60, women are only 6.0% shorter than men (Greil & Lange, 2007). Our results are therefore consistent with other data. Similar results were obtained in Germany, where in cross-sectional research conducted among children and adults from birth to age 60, it was shown that the level of height dimorphism increased until age 30, after which it began to decrease (Greil & Lange, 2007). Similarly, in Austrian research conducted among individuals between 20 and 85 years, it was demonstrated that the level of height dimorphism was the highest in the youngest age group, and began to decrease starting approximately age 30. Interestingly, in these studies, it has been demonstrated that the level of body mass dimorphism increases with age, but the rate of change in body mass and height results in a decrease in BMI dimorphism (Peter et al., 2014).

A slightly varying result was achieved in a Norwegian cross-sectional study, conducted among 20–80-year-olds. These researchers showed that the level of height dimorphism increased throughout the analysed period, while the level of body mass dimorphism decreased from around the age of 30 (Drøyvold et al., 2006). Contrastingly, in longitudinal research conducted in the USA, it was noted that the level of height dimorphism among individuals above the age of 50 increased with age (Gallowye et al., 1990), while in research performed in the Netherlands, the opposite phenomenon was exhibited. It was shown that the level of height dimorphism increased until approximately the age of 30, and then began to slightly decrease (Nooyens et al., 2008). In a longitudinal study conducted in Sweden, It has been shown that the level of body dimorphism in terms of body massiveness (assessed using BMI) initially increased until around the age of 30 and then began to decrease (Caman et al., 2013). Similar results were obtained in a Norwegian study, which found that body mass dimorphism in individuals aged 20–35 did not change, but began to increase around the age of 35, whereas the level of body massiveness dimorphism slightly decreased (Nooyens et al., 2008).

Analysing differences in body fat levels and its distribution, we noted that up until adolescence, the examined girls had greater body fat under the scapula, on the triceps and in the abdomen than the men. The level of body fat dimorphism increased during the analysed period, reaching its highest values in adolescence. In adults, the level of dimorphism decreased with age, reaching the lowest values in the oldest group. Importantly, in both the 32–34- and 50-year-olds, men had greater body fat under the scapula and in the abdomen (Fig. 3). These results appear to confirm the observations of the researchers mentioned earlier.

It is known that body fat decreases in both sexes between the ages of 1 and 6, and then increases more rapidly in girls and to a lesser extent, in boys. During puberty, an even greater contrast in the pattern of body mass gain is evident between girls and boys. In this period, girls experience primarily increased body fat, with a slight increase in lean mass, while for boys, the opposite phenomenon is observed. These differences are primarily due to steroid hormone levels. In adults, women exhibit greater lower limb fat than men, with similar levels of upper limb and trunk fat (Wells, 2007). Therefore, in our study, we found that the level of dimorphism in body fat began to decrease after puberty. The increase in abdominal fat in males is also consistent with the observations of other authors. In research conducted in the Netherlands, it was shown that males accumulate abdominal fat after puberty (Seidell et al., 1988). Similar results were obtained in Japan, where researchers demonstrated that post-pubertal men accumulate abdominal fat 2.5 times more intensely than pre-menopausal women. Visceral fat accumulation in women increases only at the onset of menopause (Kotani et al., 1994). In our study, the increased abdominal fat in the men may have been due to the fact that the examined women were just entering the phase of menopause.

In our research, we used arm strength measurements to analyse ontogenetic changes in physical fitness among males and females in terms of sex differences (this measurement is considered one of the best biomarkers (predictors) related to the aging process with regard to the musculoskeletal system (Rezaei, 2024). We noted that the males had greater strength in their stronger arm than the females. The differences between the sexes were smallest in the youngest age group, increasing with age up to 32–34 years. In the oldest participants, these differences slightly decreased (Fig. 1). Similar results were achieved in the USA for research carried out among adults aged 18–85. It was demonstrated that men dominated in this trait throughout the analysed period, and the strength of both the dominant and non-dominant arms decreased with age. However, sex differences remained similar until age 70, and their reduction was observed later than in our study, around the age 75 (Wang, 2018). In the case of research conducted in the UK, it was also observed that both men and women had similar arm strength until puberty. After this period, the strength in men increased more rapidly, reaching its peak between the ages of 29 and 39. In women, the increase in arm strength was less rapid after puberty, reaching its peak between the ages of 26 and 42. In subsequent years, arm strength in women and men, as well as the sex-related differences, decreased (Dodds, 2014). This declining dissimilarity may be related to the fact that the aging process of muscle tissue, which results in a decrease in muscle mass and, consequently, muscle strength, begins—on average—around the age of 45 (Janssen, 2000). However, the process of muscle strength loss is greater in men than in women (men lose more muscle strength than the latter) (Goodpaster et al., 2006).

However, our observations regarding the level of sexual dimorphism measured using another criterion of physical fitness—explosive lower limb strength—showed that its level increased with age, reaching its highest level (Fig. 1) in young people, i.e., at the age of 17, after girls had completed puberty and before boys had finished growing in height.

Similar results were obtained in Spain, where the influence of selected factors (e.g. sex, age, level of physical activity) was analysed on the standing long jump distance. The study results indicated that sex played a significant role in differentiating this characteristic, which is likely due to differences in body composition (lean body mass content), muscle strength and neuromuscular as well as glycolytic efficiency (Mayhew et al., 1990). It is probable that age has significant impact on standing long jump distance in children, as their central nervous system is maturing, which may play a role in muscle strength. Anthropometric factors (i.e. body height and mass) and kinematic variables may also significantly influence performance of fitness tests in children (Fernandez-Santos et al., 2017). However, in adults, cognitive decline appears to take time to manifest itself in changes related to physical performance (i.e. slower movements or reduced strength due to the natural aging process) (Grosprêtre et al., 2018; Marin-Jimenez et al., 2024). Our study results seem to confirm these relationships and show that age-related changes in physical fitness dimorphism are similar to changes in overall body composition (body height, mass and their proportions – BMI), as well as shoulder width and upper arm circumference. Although there is greater trunk fat in adulthood (32–34 years) and in old age (50–52 years), males still clearly dominate the results of fitness tests.

Undoubtedly, the study has a few limitations. Its drawbacks include the small sample size and the restricted number of analysed anthropometric characteristics. The influence of socio-economic factors on dimorphism was also not taken into account, because the population came from areas with standard housing conditions, school facilities, and relatively homogeneous living conditions, presenting a certain population model characteristic of larger industrial centers in Poland (Bochenska and Chrzanowska, 1993). Its advantage, however, is that it is a longitudinal study conducted annually from age 6 and 8 to age to 18, then at age 30–32 and later, at 50–52 years of age.

Conclusions

Based on the conducted research and the assessment of sexual dimorphism in individuals aged 8, 13, 17, 32–34 and 50–52, it can be concluded that:

1. Sexual dimorphism increased during development, reaching its highest level at the end of adolescence, particularly in terms of traits related to the differently developed fat and muscle distribution in both sexes.
2. Final dimorphism, however, develops later (as confirmed by our studies of people aged 32–34) and concerns bone characteristics (body height, shoulder width), relative body mass and circumferences.
3. In adulthood, at the threshold of aging (approximately at the age of 50), a significant reduction in the degree of sexual dimorphism is noted, which results from the nature of involutional changes that differ between the sexes.

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Author contributions

All participated in the conducted research, RŻ was responsible for the concept and design of the study, critical revision of the article, and final approval of the article, MK wrote the article, AW analysed data and conducted statistical analyses.

Ethics Statement

All examinations were conducted with the written, informed consent of the parents of minor children and adult participants. Approval was also obtained from the Bioethics Committee at the District Medical Chamber in Kraków for the study in 2022 (Consent No. 65/KBL/OIL dated April 11, 2022). All procedures contributing to the study were in accordance with the ethical standards of the relevant national and institutional human research committees and with the 1975 Declaration of Helsinki, as revised in 2008.

Data availability statement

Data are available from the corresponding author on reasonable request.

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Conflict of interest

None to declare.

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Estimation of sex and assessment of age based on morphological variations of the atlas vertebra (C1) using Cone Beam Computed Tomography: A retrospective study

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Abstract

Background

The atlas (C1) vertebra joins the cervical column to the cranial base and differs anatomically from other cervical vertebrae. Skeletal analysis may provide the only way to assess biological sex and age in poorly preserved and decomposed remains to estimate their biological profile. It is thus essential that methods are devised that allow such estimates from a wide range of bones.

Aim

This study applies Cone Beam Computed Tomography (CBCT) to evaluate whether the C1 vertebrae can be used in estimating age and sex.

Materials and Methods

CBCT of 61 male and 61 female subjects from South India with an age range of 20-60 years were included in the study, and C1 vertebrae were measured using axial and coronal sections. Data were analysed to generate an equation to predict age according to independent variables using linear regression, while discriminant analysis was used to derive an equation that classifies the values into either biological sex.

Results

Male subjects showed higher maximum anteroposterior diameter, maximum transverse diameter, and the distance between the base of the skull and the anterior tubercle than females (p=0.001). The highest standard error for males was observed in the maximum anteroposterior diameter. The base of the skull to the anterior tubercle had the highest standard error among female subjects. The base of skull to posterior

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tubercle had the lowest standard error for males, while the angulation from the transverse to the anterior tubercle had the least standard error for females. The accuracy of sex classification was 89.3%. However, parameters did not demonstrate sufficient reliability for age estimation.

Conclusion
The presented parameters may be used for sex determination in forensic identification and other medico-legal practices. In contrast, these parameters are not reliable for age estimation in our sample.

Keywords: forensic identification, forensic anthropology, morphometrics, vertebral morphology

Introduction

When examining unidentified skeletal remains, sex and age estimation are crucial components of constructing a biological profile. According to studies on sex prediction, the skull and pelvic bones have a high accuracy rate (Sertel-Meyvaci et al. 2024). Yet, due to a range of circumstances in the burial site or other occurrences, like disarticulation, scattering, and commingling, skeletal remains discovered in archaeological or forensic contexts are frequently damaged or lacking. The development of techniques that enable the determination of sex and age from a variety of skeletal components is crucial, especially when dental elements are missing in the exhumed or decomposed remains (Marlow & Pastor, 2011). While major bones (such as the skull, pelvis, femur) are frequently recovered at crime scenes, where the vertebrae are also discovered, they may have potential in biological profile reconstruction (Sertel-Meyvaci et al., 2024; Singla et al., 2015). In many situations, including mass disasters, vertebrae are often best-preserved skeletal bones (Hora & Sládek, 2018). The atlanto-occipital joint, where the occipital bone articulates with the first cervical vertebra, the atlas (C1), permits head motions. Because of its unique shape, it may be easily identified from the other vertebrae. Since vertebral dimension measurements are thought to be some of the most accurate indicators of sex, following pelvic measurements (Hora & Sládek, 2018), in this study we focus on the C1 atlas.

With the advent of 3D Cone Beam Computed Tomography (CBCT) imaging, concomitant high-resolution images allow accurate and reproducible analysis of the morphometric parameter of skeletal structures overcoming the limitations of 2D imaging, along with true 1:1 anatomic representation and economical advantage when compared to Computed Tomography (CT) and/or 2D imaging (MacDonald & Telyakova, 2024). The C1 atlas vertebrae can be clearly visualised in a 3D full Field of View (FOV) maxillofacial CBCT scans (Oliveira, 2025), which are the imaging mode in our study. The aim is to analyse whether CBCT scans of C1 vertebrae can be useful in age and sex estimation, especially in forensic contexts.

Materials and methods

Ethics clearance for this study was obtained from the AB Shetty Memorial Institute of Dental Sciences Institutional Ethics Committee (Ref. No. ETHICS/ABSMIDS/594/2025). Full CBCT FOV images spanning the period of April 2024 to April 2025 were obtained from the archives of the Department of Oral Medicine and Radiology at our institution. The Department of Oral Medicine and Radiology uses the CBCT unit Planmeca Promax 3D Mid variant. Images for 122 subjects were obtained and categorised into two groups: 61 males (mean age

36.1 ± 13.7 years) and 61 females (mean age 35.4 ± 12.9 years), constituting age ranging from 20 to 60 years. All these subjects met the inclusion criteria: i.e. having full FOV images and falling in the 20–60 years age range. Patients with history of mandibular fractures, and scans with errors, metal artifacts, and/or other pathology were excluded from the study. Planmeca Promax 3D Mid software was used to view the CBCT images.

Measurements of the atlas and from the base of the skull were taken using the axial and coronal sections in the CBCT images (Table 1; Figures 1–2). The distance in millimetres between the axial sections for the parameter AB represents the maximum transverse width of the atlas vertebra and CD represents the maximum anteroposterior width of the atlas vertebra. Subsequently, the distance in millimetres in the coronal section the parameter DF represents the vertical distance from the anterior tubercle to the base of the skull and CE represents the vertical distance from the posterior tubercle to the base of the skull. Also angle ACB and angle ADB were measured.

The data were analysed using SPSS for Windows v. 26.0, IBM Corp., Armonk, NY. Sexes were compared using discriminant analysis. Linear regression was used to generate the equation predicting age according to independent variables. An equation classifying values into either sex was obtained using discriminant analysis. $p \leq 0.05$ was the level of statistical significance.

Table 1. Description of the atlas measurement landmarks. See Figures 1 and 2 for illustration of the measurements.

SL NO	Landmark	Description
1.	Landmark A	The most lateral point of the right transverse processes
2.	Landmark B	The most lateral point of the left transverse processes
3.	Landmark C	Most anterior point on the anterior tubercle
4.	Landmark D	Most posterior point on the posterior tubercle
5.	Landmark E	Base of the skull-anterior in line with C
6.	Landmark F	Base of the skull-posterior in line with D

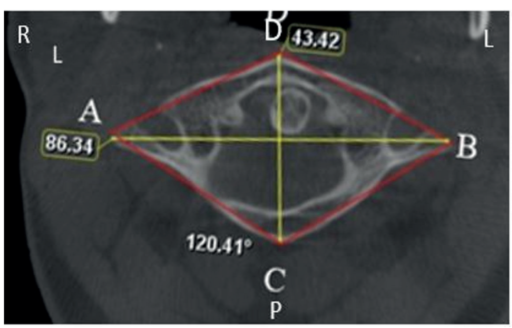

Figure 1. Image of the atlas with landmarks used for measurements. AB: Maximum transverse width, CD: Maximum anteroposterior width in mm, Angle ACB, and Angle ADB. See Table 1 for anatomical definitions of the landmarks.

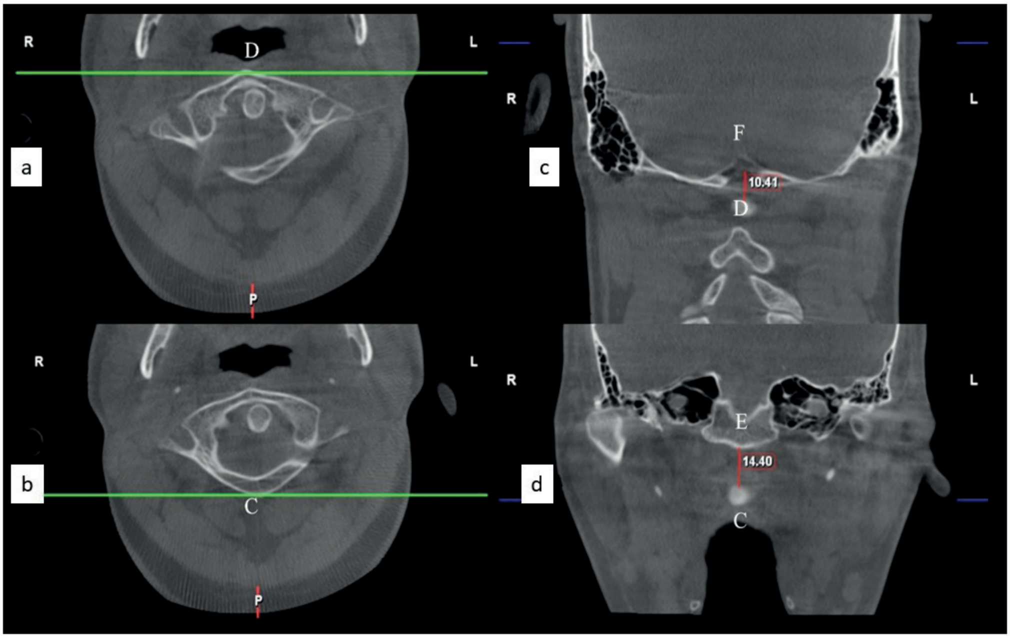

Figure 2. Composite image of the atlas (a–b) and the base of the skull (c–d) with landmarks used for measurements in this study. DF: Anterior tubercle to base of skull, CE: Posterior tubercle to base of skull. The DF and CE measurements shown are in mm. See Table 1 for anatomical definitions of the landmarks.

Results

Sex comparison

When comparing the sexes, for morphometric measurements in millimetres (mm) scale, the male participants demonstrated significantly higher values for maximum anteroposterior diameter (40.5 ± 2.7 mm vs. females 36.8 ± 3.9 mm; p = 0.001), maximum transverse diameter (75.7 ± 4.5 mm vs. females 67.3 ± 4.1 mm; p = 0.001), and distance from the base of the skull to the anterior tubercle (median 11.6 mm vs. females 10.5 mm; p = 0.001) than the female participants. Other anatomic parameters were found to be comparable between males and females (Table 2; Figure 3).

Table 2. Comparison of mean scores of different anatomic parameters of the atlas according to sex.

Parameter	Males	Females	p value
Maximum AP Diameter (CD); *mean ± sd*	40.5 ± 2.7	36.8 ± 3.9	p = 0.001*
Maximum transverse diameter (AB); *mean ± sd*	75.7 ± 4.5	67.3 ± 4.1	p = 0.001*
Angulation from transverse to posterior tubercle (ACB); *mean ± sd*	108.05 ± 7.4	106.2 ± 8	p = 0.19
Angulation from transverse to anterior tubercle (ADB); *median (IQR)*	142.1 (136–146.3)	142.4 (139.6–149.1)	p = 0.09

Parameter	Males	Females	p value
Base of skull to anterior tubercle (DF); *median (IQR)*	11.6 (10.2–13.9)	10.5 (8.2–11.9)	p = 0.001†
Base of skull to posterior tubercle (CE); *median (IQR)*	17.6 (15.2–21.2)	16 (13.6–19.8)	p = 0.06

sd – standard deviation; *statistically significant using unpaired t-test and †Mann-Whitney U test, p<0.05 statistically significant

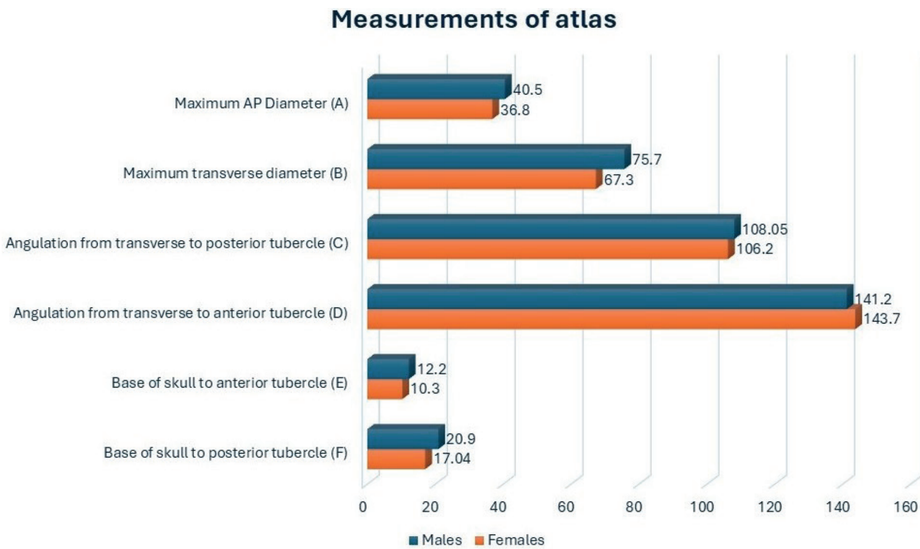

Figure 3. Graph illustrating mean scores of the different anatomical parameters of the atlas according to sex.

Age estimation

In age estimation, p=0.63 indicated that the model with the parameters used in the regression analysis was not a good predictor of age. Only 3.6% of the variance was explained by the model, which is low (Table 3). The lowest standard error of 0.08 was observed in the base of the skull to posterior tubercle, and the variable with the highest standard error was the maximum anteroposterior diameter. It was found that none of the variables in the present model had any significant impact in the prediction of age.

Table 3. Coefficient of dependent variables between residuals and regression with model summary.

	Sum of Squares	df	Mean Square	F	p value	R	R^2	SEE
Regression	779.35	6	129.8	0.726	p = 0.63			
Residuals	20576.6	115	178.9		NS	0.191	0.036	13.3
Total	21356	121						

NS – not significant, SEE – Standard Error of the Estimate

The equation derived for overall age estimation was as below:

Age (overall) = 102.77 – 0.828 × max. anteroposterior width (CD) + 0.33 × maximum transverse width (AB) – 0.144 × angulation from transverse to posterior tubercle (ACB) – 0.286 × angulation from transverse to anterior tubercle (ADB) – 0.08 × base of skull to anterior tubercle (DF) – 0.065 × base of the skull to posterior tubercle (CE).

The difference between actual age and predicted age by the equation (standard error of estimate, SEE), was 13.3 years (Table 3). A p=0.3 (males) and p=0.5 (females) indicated that the model with the variables used in the regression analysis was not a good predictor of age. Only 10% and 9.1% of the variance was explained by the model for males and females, which was very low (Table 4). Base of skull to posterior tubercle had the lowest SEE for males, while the angulation from the transverse to the anterior tubercle had the lowest SEE for females. The highest SEE for males was observed in the maximum anteroposterior diameter, while the base of the skull to the anterior tubercle had the highest SEE among female participants (Table 5).

Table 4. Coefficient of dependent variables between residuals and regression with model summary for males and females.

		Sum of Squares	df	Mean Square	F	p value	R	R^2	SEE
Males	Regression	1192.1	6	198.6	1.06	p = 0.3	0.32	0.1	13.6
	Residuals	10106.1	54	187.1					
	Total	11298.3	60						
Females	Regression	916.5	6	152.7	0.903	p = 0.5	0.302	0.091	13
	Residuals	9137.8	54	169.2					
	Total	10054.3	60						

SEE – Standard Error of the Estimate

Table 5. Regression coefficient for variables used in the model.

	B	SEE	t	p value
Constant	102.77	67.87	1.5	p = 0.133
Maximum AP Diameter (CD)	-0.828	0.607	-1.3	p = 0.17
Maximum transverse diameter (AB)	0.33	0.35	0.92	p = 0.35
Angulation from transverse to posterior tubercle (ACB)	-0.144	0.3	-0.4	p = 0.64
Angulation from transverse to anterior tubercle (ADB)	-0.286	0.2	-1.1	p = 0.24
Base of skull to anterior tubercle (DF)	-0.08	0.4	-0.17	p = 0.8
Base of skull to posterior tubercle (CE)	-0.065	0.08	-0.8	p = 0.4

SEE – Standard Error of the Estimate

Table 6 lists coefficients for variables used in the regression model for age estimation, which was as follows:

Age (Males) = 231.06 – 1.49 (*CD*) + 0.75 (*AB*) – 0.58 (*ACB*) – 0.83 (*ADB*) – 0.8 (*DF*) – 0.053 (*CE*)

Age (Females) = 71.34 – 0.968 (*CD*) + 0.065 (*AB*) – 0.073 (*ACB*) – 0.061 (*ADB*) + 1.0 (*DF*) +0.112 (*CE*)

The SEE was 13.6 years. The observed difference between actual and predicted age (~13 years) is consistent with this expected level of error.

Table 6. Regression coefficient for variables used in the model.

		B	SEE	t	p value
Males	Constant	231.06	172.5	1.3	p= 0.18
	Maximum AP Diameter (CD)	-1.49	1.5	-0.9	p = 0.33
	Maximum transverse diameter (AB)	0.75	0.79	0.94	p = 0.34
	Angulation from transverse to posterior tubercle (ACB)	-0.58	0.77	-0.74	p= 0.45
	Angulation from transverse to anterior tubercle (ADB)	-0.83	0.57	-1.44	p = 0.15
	Base of skull to anterior tubercle (DF)	-0.8	0.65	-1.2	p = 0.21
	Base of skull to posterior tubercle (CE)	-0.053	0.08	-0.6	p = 0.54
Females	Constant	71.34	76.2	0.93	p = 0.35
	Maximum AP Diameter (CD)	-0.968	0.66	-1.4	p = 0.14
	Maximum transverse diameter (AB)	0.065	0.5	0.12	p= 0.9
	Angulation from transverse to posterior tubercle (ACB)	-0.073	0.3	-0.21	p = 0.83
	Angulation from transverse to anterior tubercle (ADB)	-0.061	0.2	-0.21	p = 0.8
	Base of skull to anterior tubercle (DF)	1.006	0.7	1.2	p= 0.2
	Base of skull to posterior tubercle (CE)	0.112	0.3	0.33	p= 0.7

Sex estimation

To compute the overall classification accuracy for sex estimation, 56 of the 61 male individuals and 53 of the 61 female subjects were correctly classified. Consequently, in total, 109 out of 122 patients were accurately classified. Hence, 89.3% of the participants were accurately classified by the discriminant function based on their sex as below:

Total accuracy = (56 men + 53 females) / 122 total cases = 109 / 122 = 0.8934 (89.34%).

For sexual dimorphism, the eigenvalue of 1.183 in the present analysis suggested that this function was effective in classifying values based on sex. In addition, a canonical correlation of 0.736 suggested that the canonical variates were effective in classifying values in groups (males and females). A Wilk's Lambda of 0.458 indicated that the discriminant explained a moderate proportion of variance and was moderately effective in classifying values (Table 7).

The discriminant functions at group centroids for sex estimation were -1.079 for females and 1.079 for males. A discriminant score less than 0 classifies the values as females, and a discriminant score more than 0 classifies the values as males (eigenvalue = 1.183, correlation = 0.736, Wilks' Lambda = 0.458, p=0.001).

Table 7. Discriminant analysis for the prediction of sex

Variables	Coefficients	Wilki's Lambda	Constant
Maximum AP Diameter (CD)	0.057	0.458	-13.289
Maximum transverse diameter (AB)	0.218		
Angulation from transverse to posterior tubercle (ACB)	-0.043		
Angulation from transverse to anterior tubercle (ADB)	-0.007		
Base of skull to anterior tubercle (DF)	0.084		
Base of skull to posterior tubercle (CE)	0.007		

The canonical functional discriminant equation was (Table 7):

Sex = 0.057 (CD) + 0.218 (AB) – 0.043 (ACB) – 0.007 (ADB) + 0.084 (DF) – 0.007 (CE) – 13.29.

The classification accuracy of males (n=61) was: predicated males 56 (91.8%), predicated females 5 (8.2%). For females (n=61), predicated males were 8 (13.1%), while predicated females were classified in 53 cases (86.9%).

Discussion

The C1 vertebra is situated in a crucial region near the medulla oblongata's essential centres. It does not have a centrum, or vertebral body. With a longer posterior arch and a short anterior arch connecting them in the front, the vertebral arch has changed to create a thick lateral mass on each side. The lower articular surface is rounded or oval and almost flat, whereas the upper is kidney-shaped and concave (Thakur et al., 2022). The atlantal ring is formed by the superior and lateral masses on each side, as well as the anterior and posterior arches of the atlas. Three-fifths of the atlantal ring's circumference is made up of the posterior arch. A broad groove for the vertebral artery and venous plexus is located directly beneath the superior surface of the posterior arch. The ligamentum flava attaches to the inferior border, while the posterior atlanto-occipital membrane attaches to the superior border. A simple spinous process that has been roughened to accommodate *ligamentum nuchae* attachment is the posterior tubercle (Muralimohan et al., 2009).

The present study describes CBCT-derived morphometric parameters of the C1 vertebra to develop discriminant and regression functions for sex and age estimation in an adult population aged 20–60 years, which can be used in forensic anthropology. In our study, maximum anteroposterior diameter, maximum transverse diameter, and distance from base of skull to anterior tubercle were significantly larger in males. The discriminant function had high accuracy (canonical correlation = 0.736, Wilks' Lambda = 0.458, group centroids ±1.079), whereas the age prediction model explained very little variance (~3.6% overall), with large standard errors (~13 years) and were not statistically significant. In this study, in the linear dimensions (parameters AB, CD, and DF) there were notable sex differences, with males consistently having greater measurements than females. Although total size varied by sex, structural orientation and relative angulation were constant, as evidenced by the lack of significant differences in angular measurements (ACB and ADB) and posterior distance (CE). These results demonstrate sexual dimorphism in several C1 vertebral morphometric parameters, which most likely reflects variations in male and female skeletal development and biomechanical adaptation.

In a previous study by Marino et al. (1995), examining 100 dry atlases, sex determination was examined using discriminant function analysis and it could be made with 77–85%. Similarly, we analysed 122 C1 vertebrae for the estimation age and sex, showing that sample size >100 is needed for successful sex estimation. In a study by Padovan et al. (2020), atlas measurements suggested sexual dimorphism, with logistic regression based on two measurements achieving 81% success in a Brazilian population. Sertel-Meyvaci et al. (2024) examined 22 CBCT atlas parameters in 290 individuals of Turkish population and achieved sex classification accuracies in the range of 82–91%. They also found most dimensions significantly larger in males (Sertel-Meyvaci et al. 2024).

Our study was performed on a South Indian population, and we found that the cross-validated classification accuracy for sex was 89.3%. Our study values also depicted increased mean values for male subjects in parameters AB, CD, and DF. The systematic review by Rohmani et al. (2021) showed that vertebrae (especially cervical vertebrae including atlas and axis) tend to display measurable sexual dimorphism, though prediction accuracy varies across populations, vertebral levels and measurement types. In a study conducted by Poodendan et al. (2023), the C1 vertebrae of identified skeletons ($n = 104$, males [n, 54], females [n, 50]) accurately predicted sex, which our findings also confirm. Future research should be aimed to validate our model using a larger, independent sample from the same population to improve reliability and forensic applicability. Hence, it may be derived from this research that these C1 measurements may be applied only in sex estimation for forensic utility.

The results of the regression models for age prediction performed poorly in our study. The C1 morphometric characteristics only described a very small percentage of the age variance, according to the coefficient of determination (R^2 = 3.6%). More significantly, SEE of 13 years is above permissible limits for forensic age assessment as the difference is incredibly high. This kind of inaccuracy renders the derived equations impractical and untrustworthy for use in real time forensic applications. This implies that the specific C1 morphometric characteristics employed in this study are not appropriate predictors for determining an adult's chronological age. It is suggested that further research may be focused on population specific studies with larger sample size to attain a strong formula in support of these parameters for age estimation.

Conclusion

Accurate sex estimation is imperative for successful forensic identification, and the unique features of the atlas bone make it advantageous in sex estimation. Our findings demonstrated that the measurements of the maximum anteroposterior diameter, the maximum transverse diameter, and the distance between the base of the skull and the anterior tubercle were significantly higher among male participants when compared to female participants. Therefore, the current model (equation) accurately classified values into males and females.

However, the attempts to estimate chronological age from the same morphometric variables proved weak and unreliable. Thus, in forensic/archaeological contexts, atlas metrics may be valid for sex estimation when better bones are not available, but they should be supplemented by data for age estimation supported by research on a larger population-specific sample size.

Contributions from individual authors

TSD was the lead researcher, performed the data collection, compilation and statistical analysis, provided materials for the study and wrote the manuscript; KR was the co-lead researcher, conceived the concept of the study and design and did critical revision of the manuscript for important intellectual content. Both VA and BM carried out revision of the article. All authors discussed the results and contributed to the final manuscript for publication.

Ethics Statement

Ethical clearance was obtained from the Institutional Ethics Committee of AB Shetty Memorial Institute of Dental Sciences (Ref. No. ETHICS/ABSMIDS/594/2025).

Data availability statement

Due to ethical restrictions on sharing patient data, the complete dataset cannot be made publicly available. Researchers may seek ethics approval and request access to anonymized data by contacting the corresponding author.

Financial Disclosure

None to declare.

Conflict of interest

None to declare.

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