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Pulmonary pathologies: bioarchaeological insights from the adult individuals of the church of San Colombano, Bobbio

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Abstract

INTRODUCTION

The Church of San Colombano in Bobbio, Italy, represents one of the most important centers of early medieval monasticism in Europe and offers a valuable context for bioarchaeological research. Among the most significant discoveries is Tomb 1, a deep, multi-use burial chamber containing commingled remains of numerous individuals. The assemblage provides an opportunity to investigate health conditions and lived experiences within a medieval monastic community.

STUDY AIM

This study aims to investigate external rib lesions in adult individuals interred in Tomb 1, with particular attention to pathological alterations potentially related to respiratory disease, trauma, or nonspecific inflammatory processes, while also reconstructing aspects of the individuals' biological profiles.

MATERIALS AND METHODS

Anthropological analysis was conducted on the osteological remains recovered, comprising a minimum of 11 adults. Standard methods were applied for sex and age-at-death estimation, while rib preservation and fragmentation were assessed following established protocols. Macroscopic paleopathological examination focused on ribs, with detailed photographic documentation used to record surface alterations, new bone formation, and degenerative changes.

RESULTS

Five adult individuals preserved rib fragments suitable for pathological assessment. Observed lesions include periosteal new bone formation, microporosity, striations, widened costal grooves, and degenerative changes at articular facets. Notably, most alterations affect the ventral rib surface, while visceral involvement is limited and focal. Vertebral remains show degenerative changes but no clear evidence of infectious destruction.

Original article

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CONCLUSIONS

The predominance of external rib surface lesions, combined with the absence of osteolytic changes, suggests that healed trauma, mechanical stress, or chronic nonspecific periosteal reactions are more likely than classic pleuro-pulmonary infections such as tuberculosis. Although definitive diagnoses are precluded by fragmentation and commingling, the Bobbio assemblage highlights the interpretative complexity of rib pathology and underscores the importance of cautious, contextualized approaches in paleopathological research on medieval populations.

KEYWORDS: bioarchaeology, paleopathology, rib lesions, respiratory disease, Bobbio-San Colombano abbey, medieval population

Introduction

The Church of San Colombano in Bobbio (PC) represents a site of exceptional historical and cultural importance, as well as one of the most significant centers of early medieval monasticism in Europe, also providing a rich context for bioarchaeological and anthropological research. Founded in 613 CE through the joint initiative of the Irish monk Columbanus and the Lombard king Agilulf, the abbey soon emerged as a major religious and cultural hub in medieval Europe (Conversi & Destefanis, 2014). Strategically located in the Piacenza Apennines, the institution was not only a focal point of religious and cultural life but also played a significant role in regional politics and territorial organization during a period of profound transformation (Conversi & Destefanis, 2014; Conversi & Destefanis, 2017).

In 2015, the San Colombano complex was the subject of the first systematic archaeological investigation, carried out under the joint scientific direction of the University of Eastern Piedmont (Department of Humanities) and the Superintendency for Archaeological Heritage of Emilia Romagna. The excavation specifically involved the central section of the church's main nave.

These studies have revealed a complex history of the church and its associated funerary practices. Among the most significant discoveries is Tomb 1 (T1), a brick-built burial chamber originally covered by

a lowered-arch vault. Located west of the medieval entrance, T1 is part of a group of five tombs (T1–T5) that have lost their original covers and were later filled with construction debris from the building of the Renaissance church. The western side of T1 is slightly oblique in relation to the orthogonal layout of the structure, while the southern side is reinforced with brick fragments and mortar, forming the outer northern wall of Tomb 2. The coffin-shaped chamber is relatively long and narrow (2,05 × 0,65 m) and very deep, reaching about 1,45 m. Remains of a brick arch vault are preserved along the eastern side; however, the cover was rebuilt with mortar different from the original, probably after repeated openings and resealings over time. The tomb shows clear evidence of alterations, particularly in the upper sections of its perimeter walls. It is possible that the deeper parts of the structure belong to an earlier phase than the surrounding tombs, which were built successively. The base of the tomb lies below the walking surface, *cocciopesto*, and mosaic floor levels, pointing to a complex stratigraphy. In its final construction phase, based on building techniques and materials, the tomb can be dated to the late Middle Ages.

Beneath the fill layer, a burial deposit was identified containing several individuals in anatomical connection, with at least 11 adults and 10 non-adults recovered (Figure 1) (Conversi & Destefanis, 2017). All were buried with their heads oriented westward.

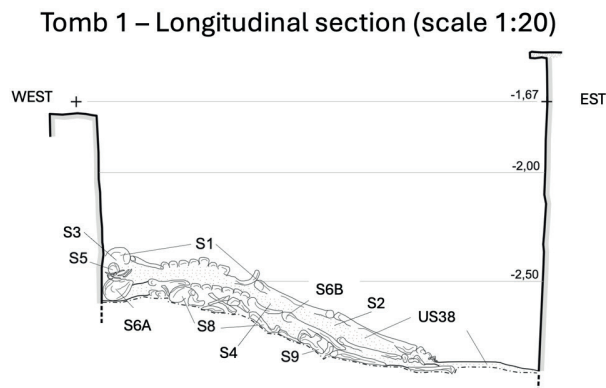


Figure 1. Schematic representation of the deposition of the individuals in Tomb 1 at the time of discovery and recovery (modified from Conversi & Destefanis, 2017)

Although the investigation could not be completed due to safety concerns linked to the considerable depth of the structure, taphonomic analysis suggests that T1 was not an ossuary but rather a multiple-use tomb employed continuously over a defined period of time.

Detailed anthropological analyses of the osteological material focused on reconstructing the biological profiles of the individuals, including sex, age at death and evidence of pathological conditions. The bioarchaeological study of these remains offers a window into the health, living conditions, and broader socio-environmental challenges faced by the medieval population.

This research focuses on the adult individuals interred in Tomb 1 of the Church of San Colombano, with particular attention to suspected respiratory pathologies. By examining skeletal evidence from the ribs, the study aims to reconstruct the health profiles of these individuals, shedding light on the challenges they faced in life.

This focus was chosen because lesions affecting the ribs, often associated

with respiratory disease processes, are frequently overlooked or considered secondary in osteoarchaeological analyses. However, these skeletal markers can provide valuable insights into pulmonary conditions and the overall health status of past populations. In this context, the evaluation of rib lesions was considered particularly informative for exploring potential respiratory pathologies among the individuals interred in Tomb 1.

Moreover, the analysis of these pathological indicators also contributes to a broader attempt to understand the cultural and funerary context of this burial assemblage. Given the absence of detailed historical documentation for this specific funerary context, the osteological evidence represents one of the few available sources through which aspects of the individuals' health and the circumstances surrounding their burial may be explored.

Materials and methods

The anthropological study began with an examination of the morphological and morphometric characteristics observable

on the skeletons to estimate the biological profile, encompassing the set of biological traits of each individual. Standard anthropological data sheets were compiled for every individual interred to gather the most comprehensive dataset possible for each burial. Alongside standard analytical protocols, district-specific methods were employed for anatomical areas characterized by extensive fragmentation, with the aim of optimizing data collection and interpretive potential.

A visual assessment of skeletal preservation was conducted using the HumanOS platform (<https://www.humanos.cnrs.fr>) to document the degree of completeness and fragmentation of different anatomical regions. In cases where skeletal districts such as the rib cage or the vertebral column were extremely fragmented, the entire region was classified as “undetermined”. This methodological choice was adopted when individual fragments could not be reliably assigned to specific anatomical elements, sides, or vertebral classes. Consequently, these regions were recorded as highly fragmented assemblages rather than as incomplete but serializable anatomical units, as their preservation state did not allow for accurate anatomical attribution or seriation.

Morphological methods applied in this study included the observation of specific sexually dimorphic features (Acsádi & Nemeskéri, 1970; Phenice, 1969). Additionally, the DSP (Diagnose Sexuelle Probabiliste – Probabilistic Sex Diagnosis) method was employed, which is a probabilistic diagnostic tool based on discriminant analysis, comparing metric data from the iliac bone against a reference database of measurements from various global populations (Murail et al., 2005). In cases of partial or minimal skeletal preservation, particularly when

both the cranial and pelvic regions were absent, other morphological and metrical techniques were used (e.g. Bass, 1995; Rogers, 1999).

For age-at-death estimation, the sample was divided into age classes based on Buikstra and Ubelaker (1994): Young Adult (21–34 years old), Middle Adult (35–49 years old) and Old Adult (50+ years old). When skeletal preservation did not allow for reliable estimation, individuals were classified as generally adult (Ad).

The estimation of age-at-death for adults relied primarily on the degree of articular degeneration of the auricular surface of the ilium (Buckberry & Chamberlain, 2002; Lovejoy et al., 1985) and the surface of the pubic symphysis (Brooks & Suchey, 1990; Hartnett, 2010a). Changes to the surface and margins of the sternal end of the ribs were also assessed (Hartnett, 2010b; İşcan et al., 1985). Where possible, stature was estimated using the formulas proposed by Trotter and Gleser (1952).

For the description and recording of the ribs, we followed the methodological framework proposed by Davies-Barrett et al. (2018), while retaining the classification system introduced by Roberts et al. (1994) for the description of rib fragments. In addition, the approach outlined by Knüsel and Outram (2004) was applied to tabulate and code the preserved portions of the ribs. The combined use of these three methodologies was adopted in order to achieve a more accurate and comprehensive description of rib preservation. Specifically, the approach proposed by Davies-Barrett et al. (2018) was employed to assess the degree of rib fragmentation. The classification system introduced by Roberts et al. (1994) was used to assign rib fragments to one of the three anatomical categories (upper, middle, lower);

due to the high level of fragmentation observed in the assemblage, this simplified classification was considered the most appropriate and reliable. In addition, the method outlined by Knüsel and Outram (2004) provides a systematic coding system to quantify and tabulate the preserved anatomical portions. Together, these approaches enable a nuanced assessment of both fragmentation patterns and overall preservation state.

Macroscopic paleopathological investigations were conducted through direct visual observation of bone alterations and detailed imaging techniques. High-magnification photographs were captured using a Canon 50D camera equipped with a Canon 100mm macro lens, allowing for precise documentation of skeletal anomalies.

To support the interpretation of the observed lesions, the rib pathological changes were evaluated through comparison with previously published clinical and bioarchaeological studies addressing pathological alterations of the rib surface. In particular, the analysis considered both documented osteological collections and archaeological case studies in which rib lesions have been associated with pulmonary conditions.

Special attention was given to pathological alterations affecting the external surface of the ribs. The observed features were therefore assessed within a differential diagnostic framework, taking into account the morphology, distribution and localization of the lesions as described in the relevant literature.

Results

The archaeological excavation conducted at Tomb 1 of the Church of San Colombano initially led to the recovery of

nine skeletons. Anthropological analysis was performed on the exhumed individuals, provided to the authors for study, with the aim of defining their basic biological profiles and identifying major pathologies.

The analysis revealed that the individuals, initially considered nine adults, actually represent 11 adults (Figure 2 and Table 1) and a total of 10 non-adults. Specifically, Subject 7, represented only by the lower limbs and pelvis, was determined to be part of Subject 3, whose upper body was the only portion previously recovered. Consequently, these remains were grouped under Subject 3. Subject 6 was divided into 6a and 6b because two distinct individuals were identified among the skeletal remains recovered by archaeologists. Subject 5 was found to consist of multiple non-adult individuals. Within the bag labeled "filling" by the excavation and recovery team, a minimum of 3 individuals were identified, all female, based on the presence of pubic symphysis. Owing to their high degree of fragmentation and commingling, these individuals were not schematically represented in Figure 2, and their state of preservation did not allow for reliable age estimation.

Due to the fragmentary condition of the remains, it was not possible to seriate the ribs; however, lateralization was achievable in many cases. The data relating to the ribs, together with selected observations on the vertebrae, are presented below. The tables summarize the results of the descriptions coded according to the adopted methods. Fragments classified as indeterminable were affected by such a high degree of taphonomic degradation that reliable siding was not possible and were therefore grouped into broader, non-specific categories.

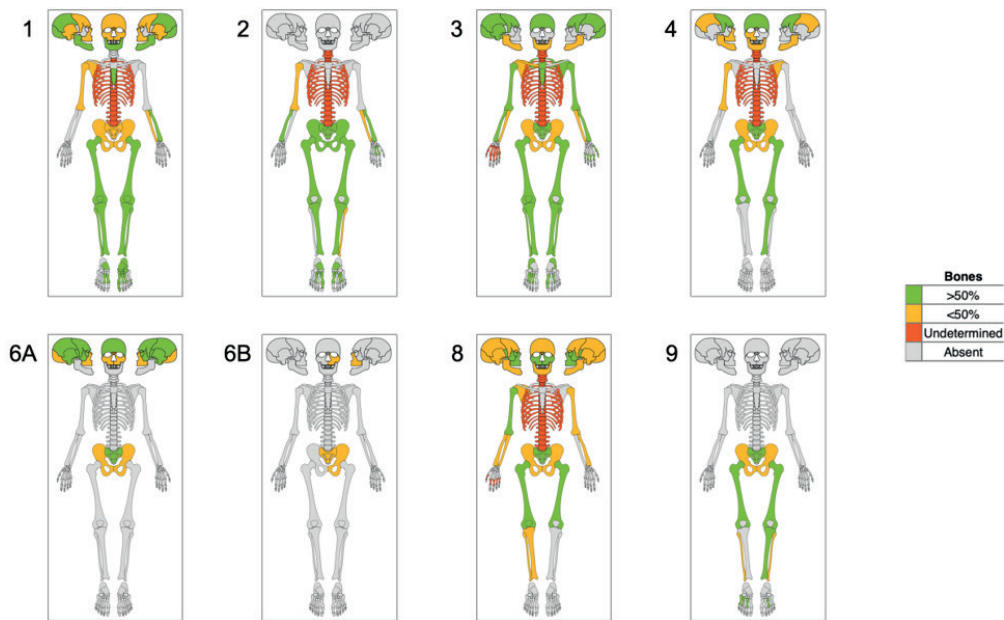


Figure 2. Visual representation of the preservation levels of bone regions

Table 1. Biological profiles of the adult individuals of Tomb 1. *ND: Not Detectable* (due to incompleteness or fragmentation). See the Materials and methods section for details on the methods used for the assessment

Subject n.	Sex	Age class	Age-at-death	Methods used	Height	Pathologies
1	M	OAd	40–50 years	Dental wear, cranial sutures	176,1±3,27 cm	Maxillary abscess, periosteal bone reaction of the external face of the costae
2	M	OAd	45–50 years	Auricular surface of the ilium, dental wear, cranial sutures	171,9±3,27 cm	Osteoarthritis, vertebral hernias, periosteal bone reaction of the external face of the costae
3	M	MAd	35–40 years	Auricular surface of the ilium, cranial sutures	175±3,27 cm	Periosteal bone reaction of the external face of the costae
4	M	OAd	40–50 years	Dental wear, cranial sutures	ND	? (see results)
6A	F	YAd	25–30 years	Auricular surface of the ilium, pubic symphysis, cranial sutures	ND	
6B	M	MAd	35–40 years	Auricular surface of the ilium, pubic symphysis	ND	

Subject n.	Sex	Age class	Age-at-death	Methods used	Height	Pathologies
8	F	YAd	20–35 years	Dental wear	ND	
9	F	MAd	25–30 years	Auricular surface of the ilium	154,9±3,72 cm	
Filling A	F	ND	ND	Pubic symphysis	ND	
Filling B	F	ND	ND	Pubic symphysis	ND	
Filling C	F	ND	ND	Pubic symphysis	ND	

Subject 1

The ribs exhibit irregularities on the external surface, primarily concentrated near the sternal extremity. These irregularities manifest as bone overgrowth (neoproduction) combined with microporosity (<1mm) (Figure 3A). On three ribs (Figure 3B), anomalies were observed on the visceral surface near the sternal extremity. Two ribs (red and green boxes of Figure 3B) display circular or curved bone projections smaller than 10mm in diameter, while the third rib (yellow box of Figure 3B) presents a linear projection parallel to the margins, approximately 15mm in length. One right floating rib shows

bone overgrowth along the margins of the external surface and an oblique groove delineated by raised edges (Figure 3C). Additionally, ribs with preserved vertebral extremities exhibit degeneration of the articular facets with lipping and microporosity (Figure 3D).

A total of eight fragmentary vertebral bodies are preserved, one attributable to an upper lumbar vertebra and the remaining fragments to thoracic vertebrae that could not be seriated (Table 2). In addition, four articular facet fragments pertaining to thoracic vertebrae are present but cannot be assigned to the vertebral bodies listed above.

Table 2. Degree of fragmentation and preservation of the ribs of Subject 1

Rib fragments	Siding	Davies-Barrett et al. (2018) – fragmentation score	Roberts et al. (1994) – most likely position	Knüsel and Outram (2004) – Zonation method
#1	right		Middle	1
#2	right		Lower	2,3
#3	left		Middle	2
#4	left		Middle	3 (with sternal end)
#5	left	3	Lower	3 (with sternal end)
#6	left		Lower	3 (with sternal end)
n.8 fragments	ND		ND	3
n.1 fragment	ND		ND	1
n.3 fragments	ND		Lower	3 (with sternal end)

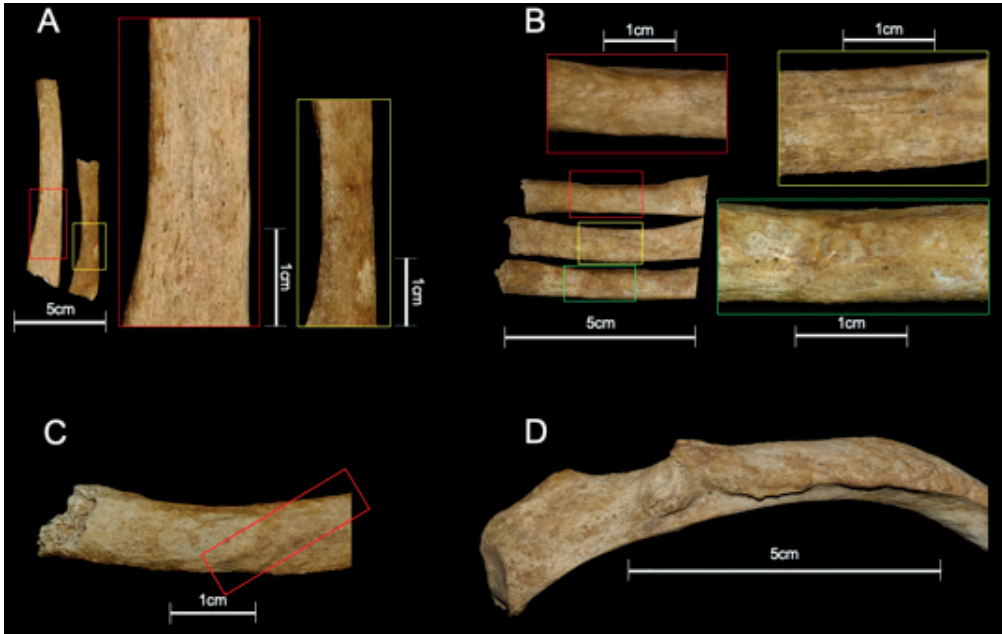


Figure 3. Subject 1, A: from the left, external view of fragments from a left and a right rib, with boxes for magnification of details; B: visceral surfaces of two left ribs (red and green boxes for magnification) and one right rib (yellow box for magnification); C: fragment of a right floating rib (oblique groove bordered with a red box); D: fragment of a left rib head

Subject 2

The ribs exhibit irregularities on the external surface, primarily near the sternal extremity, characterized by diffuse bone overgrowth with microporosity ($<1\text{mm}$) (Figure 4A). Some ribs display unique features, including oblique bands delineated by raised edges (Figure 4B) and bone spurs along the rib margins (Figure 4C). In both cases, the bone overgrowth is associated with microporosity ($<1\text{mm}$), concentrated near the tubercle (Figure 4B) or on the spurs (Figure 4C). One right rib displays a particularly wide costal groove ($\sim 15\text{mm}$), with an undulated superior margin (Figure 4D). Another right rib fragment exhibits perpendicular bone formation along the superior margin of

the visceral surface, which is relatively ordered, while the inferior margin shows disorganized deposition with diffuse microporosity ($<1\text{mm}$) (Figure 4E). Ribs with preserved vertebral extremities exhibit lipping and porosity on the articular facets (Figure 4F).

The preserved vertebral elements include lumbar vertebrae, middle and lower thoracic, and two fused cervical fragments (Table 3). The lower thoracic vertebrae exhibit degenerative changes of the vertebral bodies, characterized by the presence of osteophytic lipping. Two of these vertebrae are fused on the right side, while the immediately superior and inferior vertebrae show bony exostoses on the same side that had not yet progressed to complete ankylosis.

Table 3. Degree of fragmentation and preservation of the ribs of Subject 2

Rib fragments	Siding	Davies-Barrett et al. (2018) – fragmentation score	Roberts et al. (1994) – most likely position	Knüsel and Outram (2004) – Zonation method
#1	right	3	Upper	2,3
#2	right		Upper	3
#3	right		Middle	3
#4	right		Middle	1,2
#5	right		Middle	1,2
#6	right		Middle	1,2
#7	right		Middle	3 (with sternal end)
#8	right		Middle	3 (with sternal end)
#9	right		Middle	3 (with sternal end)
#10	right		Middle	1,2
#11	right		Middle	1
#12	right		Middle	1
#13	right		Middle	1
#14	right		Lower	1,2
#15	left		Upper	3 (with sternal end)
#16	left		Upper	2
#17	left		Upper	1,2
#18	left		Upper	1
#19	left		Middle	2
#20	left		Middle	1,2
#21	left		Middle	2,3
#22	left		Middle	1
#23	left		Middle	1
#24	left		Middle	1
#25	left		Middle	1,2
#26	left		Lower	1,2
n.19 fragments	ND		ND	3
n.14 fragments	ND		Upper, middle, lower	3 (with sternal end)

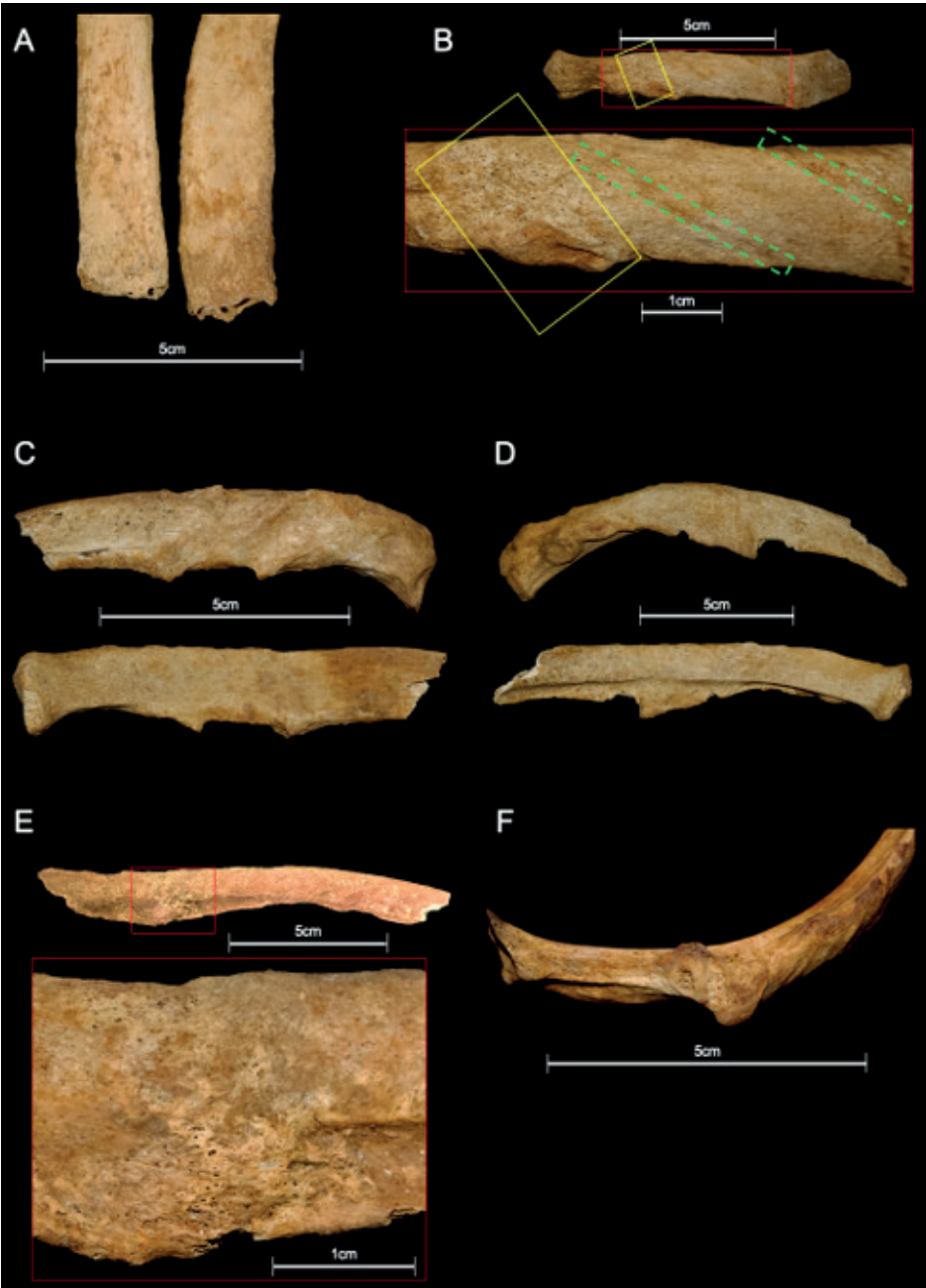


Figure 4. Subject 2, A: fragments of two right ribs' bodies, with sternal end; B: fragment of a right rib with bone overgrowth and microporosity (yellow box) and oblique bands (green dashed rectangles); C: fragment of a left rib; D: fragment of a right rib; E: right rib fragment with bone formation and microporosity (red box for magnification); F: fragment of a left rib head

Subject 3

The ribs exhibit irregularities on the external surface, primarily near the sternal extremity, characterized by diffuse bone overgrowth without microporosity (as in Figure 5A). Ribs with preserved vertebral extremities show lipping and porosity on the articular facets (Figure 5B–C). In Figure 5C, it presents an oblique groove on

the external surface with raised margins. One right rib presents an altered margin, with the superior margin featuring a curved protuberance consistent with the surrounding surface (Figure 5D). A single fragment of the vertebral arch from a cervical vertebra is preserved (Table 4).

Table 4. Degree of fragmentation and preservation of the ribs of Subject 3

Rib fragments	Siding	Davies-Barrett et al. (2018) – fragmentation score	Roberts et al. (1994) – most likely position	Knüsel and Outram (2004) – Zonation method
#1	right	3	Upper	2,3 (with sternal end)
#2	right		Upper	1
#3	right		Middle	1
#4	right		Middle	1
#5	right		Middle	2
#6	right		Middle	3
#7	right		Middle	3
#8	left		Upper	1
#9	left		Upper	1,2
#10	left		Upper	2,3
#11	left		Upper	2,3 (with sternal end)
#12	left		Middle	1
#13	left		Middle	1
#14	left		Middle	1
#15	left		Middle	1
#16	left		Middle	1,2
#17	left		Middle	3
#18	left		Middle	3
#19	left		Middle	3 (with sternal end)
n.8 fragments	ND		Middle, lower	3
n.12 fragments	ND		Middle, lower	3 (with sternal end)



Figure 5. Subject 3, A: fragment of a right rib body; B: fragment of a right rib head; C: fragment of a left rib head; D: fragment of a right rib body (red box for magnification)

Subject 4

Only a few rib fragments were attributed to Subject 4, and none of them showed pathological alterations (Table 5). The preserved cervical vertebrae include a fragment of C1, part of the body of C2, one complete cervical vertebra, and an isolated vertebral body and bifid spinous process. The thoracic vertebrae of this

individual are represented by four fragmentary vertebral bodies and ten articular facet fragments pertaining to thoracic vertebrae that cannot be assigned to the elements listed above. Three lumbar vertebrae are preserved in a fragmentary condition; among these, only L5 could be identified, preserving part of the left transverse process.

Table 5. Degree of fragmentation and preservation of the ribs of Subject 4

Rib fragments	Siding	Davies-Barrett et al. (2018) – fragmentation score	Roberts et al. (1994) – most likely position	Knüsel and Outram (2004) – Zonation method
#1	left	3	Middle	1,2
n.4 fragments	ND		Middle	3
n.2 fragments	ND		Lower	3
n.1 fragment	ND		Middle	3 (with sternal end)

Unassignable rib fragments from S3 or S4
Two fragments of left rib bodies, which could not be assigned to either subject,

display a wide costal groove (~10mm), along with small oblique grooves and cavitations (~1mm) (Table 6, Figure 6).

Table 6. Degree of fragmentation and preservation of ribs not confidently attributable to Subjects 3 and 4

Rib fragments	Siding	Davies-Barrett et al. (2018) – fragmentation score	Roberts et al. (1994) – most likely position	Knüsel and Outram (2004) – Zonation method
#1	right	3	Upper	3 (with sternal end)
#2	right		Upper	2
#3	right		Middle	2
#4	left		Upper	2
#5	left		Upper	2,3
#6	left		Middle	1
#7	left		Middle	2
#8	left		Middle	3
#9	left		Middle	3
#10	left		Middle	3
#11	left		Middle	3
#12	left		Middle	3
#13	left		Lower	3
n.26 fragments	ND		Middle	3



Figure 6. Unassignable fragments of the bodies of the left ribs (either from subject 3 or 4).

Subject 8

Only a limited number of rib fragments were attributed to Subject 8, none of which displayed evidence of pathological alterations (Table 7).

Four fragmentary vertebral bodies are preserved, three attributable to upper thoracic vertebrae that could not be seriated, while the fourth is compatible with the seventh cervical vertebra. The

remaining thoracic vertebrae are present but preserved only as vertebral bodies, making reliable seriations difficult (T2–T8 and T10–T12). The lumbar vertebrae are also present but, as with the thoracic elements, are represented solely by vertebral bodies. In addition, five articular facet fragments pertaining to thoracic vertebrae are preserved but cannot be assigned to the elements listed above.

Table 7. Degree of fragmentation and preservation of the ribs of Subject 8

Rib fragments	Siding	Davies-Barrett et al. (2018) – fragmentation score	Roberts et al. (1994) – most likely position	Knüsel and Outram (2004) – Zonation method
n.27 fragments	ND	3	Middle (?)	3
n.6 fragments	ND		Middle	3 (with sternal end)

Discussion with conclusions

Of the five individuals presenting rib fragments, it was possible to assign some elements to the corresponding side in four cases; however, in all individuals, several rib fragments were too small and fragmented to allow reliable lateralization. Three of the five individuals exhibit morphological alterations of the ribs, including porosity, striations, new bone formation, widening of vascular grooves, and, in some cases, bone production and porosity around the articular facets of the rib head.

The rib lesions observed in the medieval assemblage from Bobbio present several interpretative challenges. First, due to the fragmented and commingled nature of the skeletal assemblage, it is not possible to attribute the pathological findings with certainty to a single individual. However, the analysis followed the subdivision established during the excavation and was supported by comparison with the *in situ* documentation recorded at the time of recovery. Second, the inability to reassemble or serially align the ribs prevents any reliable determination of whether the affected elements derive from the upper, middle, or lower thoracic cage (excluding the floating ribs), although an attempt was made to assign lateralized fragments to one of these three categories. This limitation significantly hampers the reconstruction of potential clinical implications, as the location within the rib cage may influence the interpretation of the lesions. Third, the pathological evidence is not confined to a single anatomical region of the ribs: alterations are distributed from the posterior portion, close to the rib head, to the anterior segment near the sternal end.

Another noteworthy aspect is the surface distribution of the lesions. The majority of pathological changes affect the external (abdominal) surface of the ribs. In the paleopathological literature, rib lesions are more frequently described on the internal (visceral) surface, where they are commonly associated with chronic pulmonary and pleural infections, especially tuberculosis (e.g. Assis & Keenleyside, 2019; Mays et al., 2002; Nicklisch et al., 2012; Roberts et al., 1998). In such cases, new bone formation and porosity typically appear as reactive responses to pleuritis (Baumer, 2008; Davies-Barrett et al., 2018). The findings from Bobbio, however, differ in that the alterations predominantly occur on the external surface.

Exceptions to this pattern are: the widening of the costal groove, appreciable especially from the visceral surface (Figures 4D and 6), that may suggest a remodeling process potentially linked to vascular stress (Mays et al., 2002); and three ribs attributed to Individual 1 that show parallel thickenings aligned with the long axis of the rib on the visceral surface, near the sternal end (Figure 3B). These lesions differ morphologically from the external surface alterations and may indicate a localized irritative process, distinct from the other pathological changes.

Periosteal reactions represent a response of the periosteum to external stimuli, which can vary according to the intensity, duration and pace of the underlying pathological process (Assis & Keenleyside, 2019). Slowly progressing diseases tend to produce solid, compact and well-organized lesions, while chronic processes of moderate intensity may result in compact but less aggressive new bone formations (Assis & Keenleyside, 2019).

The thoracic region, due to its protective role for the heart and lungs and its close proximity to the lungs, can reflect signs of chronic respiratory disease (Baumer, 2008). However, post-mortem fragmentation of ribs often limits the observation of certain areas and affects comparability between individuals and studies (Davies-Barrett et al., 2018).

Although rib lesions are most commonly associated with pulmonary infections such as tuberculosis, other respiratory or systemic conditions can produce similar periosteal responses. Bacterial or viral pneumonia, chronic bronchitis, trauma, and neoplastic conditions may generate overlapping skeletal changes, complicating the attribution of lesions to a single disease (Assis & Keenleyside, 2019; Lambert, 2002; Molto, 1990).

In summary, the presence of periosteal reactions on archaeological ribs is a non-specific indicator of lower respiratory tract disease, useful for inferring the burden of pulmonary pathology in past populations but insufficient for a definitive diagnosis of a specific condition.

A possible differential diagnosis for the Bobbio sample is presented below.

Chronic periosteal reaction and its relevance to ribs. Because ribs lie adjacent to lungs and pleura, they frequently register thoracic insults; however, rib preservation is uneven and post-mortem fragmentation can bias which surfaces/segments are observable (Davies-Barrett et al., 2018). Despite this, periosteal change on ribs remains an underused but informative stress index in past populations (Lambert, 2002). In the Bobbio ribs, most alterations occur on the external/ventral surface rather than the visceral surface. Where the newly formed bone is compact and remodeled, a chronic peri-

osteal process is plausible (e.g., a latent infection persisting over time). Yet, because external-surface rib reactions are not specific and can be triggered by mechanical irritation (e.g., minor trauma and muscle-related strain), this category overlaps with the traumatic spectrum (Assis & Keenleyside, 2019; Davies-Barrett et al., 2018). This provides a chronic, non-specific explanation especially for smooth, lamellar, “mature” new bone.

Pulmonary tuberculosis (TB). Studies of documented collections consistently report a strong association between periosteal new bone on the visceral rib surface and TB, often interpreted as reaction to pleural inflammation; occasional shallow, circumscribed lytic foci are also described (Assis & Keenleyside, 2019; Mays et al., 2002; Nicklisch et al., 2012; Roberts et al., 1998). TB may involve the ribs through hematogenous spread, direct extension from the lung or pleura, or from spinal foci (Mays et al., 2002). In the latter case, lesions tend to affect the rib head or neck and are often associated with destructive changes, whereas other routes may involve any segment of the rib (Mays et al., 2002). Thoracic rib enlargement has been noted in chronic pleural disease clinically (Matos & Santos, 2006). In addition, spinal involvement is commonly reported in skeletal tuberculosis, typically affecting the vertebral bodies and resulting in destructive lesions, collapse, and angular deformity. In the Bobbio ribs, the predominant external-surface distribution and absence of osteolysis argue against classic pleuro-pulmonary TB presentations on ribs. No serial alignment is possible and ribs are non-attributable to individuals, which limits case-level inference; nevertheless, the pattern observed here does not match the usual visceral-surface

bias reported for TB-related rib change (Assis & Keenleyside, 2019; Mays et al., 2002; Nicklisch et al., 2012; Roberts et al., 1998). Moreover, in the Bobbio assemblage, however, the vertebrae examined do not show pathological changes consistent with spinal tuberculosis. The absence of such lesions further weakens the attribution of the observed rib alterations to TB.

Some exceptions to note include: (i) widened costal groove appreciated mainly from the visceral side (Figures 3D and 5) indicates remodeling but is not specific for TB (Mann & Hunt, 2005; Matos & Santos, 2006; Nicklisch et al., 2012); and (ii) three ribs (Individual 1) show parallel thickenings aligned with the long axis on the visceral surface near the sternal end (Figure 3B). These could reflect localized pleural or soft-tissue irritation, but without additional TB markers they remain non-diagnostic. Overall, TB is unlikely given surface distribution and absence of destructive change; cannot be completely excluded but not favored.

Other lower-respiratory infections and pleural disease (pneumonia, bronchopneumonia, chronic bronchitis, actinomycosis; pleurisy/effusion). Multiple respiratory conditions can provoke periosteal reaction on the visceral rib surface due to pleural inflammation; this includes bacterial and viral pneumonias and other agents (Davies-Barrett et al., 2018; Lambert, 2002). Historically, respiratory infections were common causes of morbidity and mortality, particularly among vulnerable groups (Molto, 1990). Pleural effusion/pleurisy is frequently cited as a driver of visceral-surface change (Nicklisch et al., 2012). In the Bobbio ribs, because the lesions are chiefly external/ventral, the expected visceral pattern is lacking.

No osteolysis is present. The three visceral thickenings near the sternal end (Individual 1) remain compatible with localized pleural irritation, but they are few and focal relative to the external-surface burden. Overall possible in principle for the small visceral subset, but the dominant external pattern makes widespread respiratory/pleural disease less likely.

Osteomyelitis. What is expected: subperiosteal spread elevates the periosteum and deposits layered new bone parallel to the shaft; disruption of blood supply may yield *sequestra* and cortical destruction (Rana et al., 2009). In the Bobbio ribs there is no macroscopic osteolysis and no necrotic morphology. The distribution across multiple ribs without clear focal destructive centers argues against classic pyogenic osteomyelitis. Overall, it is unlikely.

Hypertrophic pulmonary osteoarthropathy. A systemic process that produces bilateral, fairly symmetric periosteal reactions, classically along the diaphysis of long tubular bones, rather than isolated rib-dominant change (Rana et al., 2009). In the Bobbio ribs the pattern is not systemically widespread nor described on long bones; rib-only external change without symmetric appendicular involvement is not characteristic.

Skeletal fluorosis. It is expected a generalized osteosclerotic diathesis with dense periosteal deposition, frequent enthesophytes/osteophytes, rib enlargement, and dental changes; vertebral/trabecular sclerosis is common (Nelson et al., 2019). In the Bobbio ribs the assemblage does not present a systemic sclerotic signature or dental fluorosis pattern; rib changes are focal and surface-biased.

Environmental irritants and airway stressors. In past populations, smoke, dust, agricultural particulates, molds and crowding/poor ventilation increased susceptibility to respiratory disease (Rana et al., 2009). Muscle attachments can extend onto rib surfaces and introduce surface variability; transverse or cortical thickening can resemble enthesal or exostotic change (Davies-Barrett et al., 2018). In the Bobbio ribs these factors may explain minor visceral-side remodeling (e.g., costal-groove widening; the three parallel visceral thickenings near the sternal end in Individual 1) as localized mechanical/pleural responses, but they do not account for the predominant external-surface pattern across the assemblage.

Healed rib fractures/trauma. Rib fractures are common in archaeological series and may be multiple; healing produces periosteal new bone and callus, often more appreciable on the external surface with localized thickening and contour change (Brickley, 2006; Matos, 2009; Rana et al., 2009; Roberts et al., 1998). The morphology can be solid and organized in uncomplicated, chronic healing phases (Rana et al., 2009). In the Bobbio ribs the external/ventral predominance, irregular thickening and remodeling seen on several ribs, together with the absence of lytic destruction, fit best with healed traumatic change. The heterogeneous distribution (from near the head to pre-sternal portions) is also compatible with non-contiguous injuries accrued over time rather than a single pleural disease process. Limited serial attribution prevents demonstrating adjacency of affected ribs, but this does not contradict a trauma explanation. Overall, this is the most likely etiology for the external-surface lesions (including the reaction illustrated in Figure 4E).

Evidence of new bone formation on the external, muscular surface of the ribs is significantly less well documented as a specific pathological marker. Most periostitis related to pulmonary TB or other pleural infections develops instead on the visceral surface, where inflammatory processes directly affect the rib cortex through contact with the pleura (Nicklisch et al., 2012).

Anatomically, the external rib surface serves as the attachment site for several thoracic wall muscles, including the external, internal, and innermost intercostals, as well as the subcostals and the transversus thoracis. These muscles play essential roles in breathing by elevating or depressing the ribs, and their attachments can sometimes create irregularities or striated/nodular textures on the rib surface (Davies-Barrett et al., 2018).

Some rib surface changes, such as dense transverse cortical bone formation, may reflect enthesal activity or exostoses, complicating differentiation between mechanical and pathological processes. Moreover, while clinical descriptions of rib enlargement and destructive lesions exist, their correlation with pulmonary infections in the paleopathological record is inconsistent, as similar changes may arise from hematogenous spread or soft-tissue involvement (Nicklisch et al., 2012).

Rib enlargement, often appearing as sclerosis and thickening on ventral and visceral surfaces, may reflect chronic inflammatory changes or ossification of adjacent soft tissue or ligaments (Nelson et al., 2019). However, these features remain nonspecific, with pneumonia, bronchiectasis, metastases, osteomyelitis, and mycoses all potential alternative diagnoses (Nicklisch et al., 2012). Taken together,

the rib lesions from Bobbio underscore the complexity of paleopathological interpretation.

In medieval European skeletal studies, particular diagnostic significance has traditionally been attributed to lesions affecting the visceral surface of the ribs, especially in relation to pulmonary infections such as tuberculosis, for which a strong association with internal periosteal reactions has been proposed (Mays et al., 2002). However, medieval rib pathology is not restricted to infectious processes. Research on skeletal trauma has shown that rib fractures were relatively common during the Middle Ages and frequently associated with everyday activities, occupational stress, interpersonal violence, or accidental falls. Healed fractures may result in localized periosteal new bone formation and irregular cortical thickening, often involving the external surface of the ribs (Brickley, 2006).

Comparative studies of late medieval urban populations further support a multifactorial interpretation of rib lesions. High prevalences of nonspecific periosteal reactions have been documented in densely populated urban contexts, where mechanical stress, recurrent minor trauma, and chronic inflammatory conditions were likely exacerbated by crowding, poor air quality, and physically demanding labor (Gernay, 2015). In this context, the Bobbio assemblage expands the spectrum of rib involvement documented for medieval populations. While the literature predominantly links internal rib surface lesions to infectious disease, particularly tuberculosis, the predominance of external surface alterations observed at Bobbio is more consistent with trauma-related or nonspecific periosteal responses. Moreover, the challenges posed by the fragmentary and

commingled nature of the assemblage stress the importance of cautious interpretation: without precise individual attribution, rib seriality and thoracic context, hypotheses on the etiology of these lesions remain necessarily tentative.

This study demonstrates the potential of rib analyses to contribute significantly to the understanding of past health conditions, particularly those affecting the respiratory system. The presence of periosteal reactions, rib remodeling and other pathological alterations provides valuable, though often nonspecific, evidence for chronic inflammatory and infectious processes. However, as highlighted in the present material from Bobbio, interpreting rib lesions remains challenging for several reasons: the difficulty in assigning isolated ribs to specific individuals, the impossibility of seriating them to determine their thoracic position and the variability of lesion distribution across both posterior and anterior rib segments.

These limitations underline the importance of adopting a cautious and contextualized approach. As Rana et al. (2009) observed, in the evaluation of periosteal reactions, the primary goal should be the recognition of their presence rather than the attempt to strictly categorize their subtypes, given the considerable overlap among different etiologies. Similarly, while clinical and paleopathological literature often associates visceral rib lesions with pulmonary tuberculosis and other pleural infections, the evidence from Bobbio also involves external surfaces, which may reflect mechanical stress, trauma, or nonspecific infections rather than a direct pulmonary origin.

Taphonomic and preservation biases further complicate interpretation. As Mays (1992) emphasized, ribs are among the most fragile skeletal elements due to

their high trabecular component, often leading to poor preservation and underrepresentation in archaeological studies. This may explain why rib lesions, despite their diagnostic potential, have historically received relatively little attention (Brickley, 2006). Nonetheless, the thoracic skeleton plays a crucial role in protecting vital organs and supporting the mechanics of respiration, making pathological changes in ribs an important avenue for bioarchaeological inquiry.

Ultimately, the Bobbio assemblage illustrates both the promise and the limitations of rib paleopathology. While specific diagnoses remain elusive, the identification of rib alterations contributes to broader discussions of respiratory disease, mechanical stress and nonspecific infection in medieval populations. Future studies that integrate macroscopic, radiological, and biomolecular analyses, in conjunction with archaeological and environmental data, will be essential to refine interpretations and to better situate rib pathology within the lived experiences of past communities.

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Author contributions

Arianna Vanni and Roberta Fusco: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. Nicol Rossetti: Conceptualization, Investigation, Writing – review & editing. Eleonora Destefanis: Conceptualization, Inves-

tigation, Supervision, Writing – review & editing. Marta Licata: Supervision.

Ethics statement

All analyses were conducted with the authorization of the competent Italian Superintendency (Soprintendenza).

Data availability statement

The data supporting the findings of this study are included within the article. Additional information may be made available by the corresponding author upon request.

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Conflict of interest

The authors declare no conflict of interest.

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Secular changes in body height, body mass, and BMI among rural boys in Eastern Poland (1986–2021)

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Abstract

INTRODUCTION

Body height, body mass, and BMI are key indicators of physical development, reflecting the combined effects of genetic potential and environmental conditions. Secular changes in these traits are particularly pronounced in populations undergoing socio-economic transformation, including rural regions. Eastern Poland remains one of the economically weakest regions of the European Union, which may influence the somatic development of children and adolescents.

STUDY AIM

This study examined long-term secular changes in body height, body mass, and BMI among rural boys aged 7–15 years from eastern Poland between 1986 and 2021.

MATERIAL AND METHODS

The sample comprised 14,685 boys from five cross-sectional surveys conducted in 1986, 1996, 2006, 2016, and 2021, with sample size increasing from 1,259 to 5,599. Measurements were performed using standardized anthropometric procedures, and BMI categories were defined using Cole's international cut-off points. Statistical analyses included one-way ANOVA with Games–Howell post hoc tests, linear regression, and chi-square tests for BMI categories.

RESULTS

Significant increases were observed in all traits. Between 1986 and 2021, mean body height increased by 7.85 cm, with the largest gains among 13-, 9-, and 14-year-olds. Mean body mass rose by 5.83 kg, particularly in 14- and 15-year-olds. BMI increased by 1.21 kg/m², with the greatest changes occurring in older boys. The prevalence of overweight and obesity increased consistently across all age groups, with a marked acceleration between 2016 and 2021, while the prevalence of underweight declined slightly over the long term. Regression models confirmed systematic upward trends in all somatic traits.



Original article

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CONCLUSIONS

These findings indicate that although linear growth continues, the pattern of development is increasingly characterized by rising body mass and BMI, reflecting a shift toward a higher prevalence of overweight and obesity. This trend highlights the need for targeted public health monitoring and early preventive strategies in rural populations.

KEYWORDS: somatic development, rural population, adolescents, nutritional status, overweight, obesity, growth patterns

Introduction

Body height and body mass are fundamental indicators of somatic development, as they reflect the integrated influence of genetic predisposition and a wide range of environmental factors, including nutrition, living conditions, and access to healthcare (Lui et al., 2024). Changes in the mean values of these parameters observed across successive cohorts are referred to as secular trends and are considered important indicators of the biological status of populations and their adaptation to shifting socio-economic conditions (Fudvoye & Parent, 2017; Pop et al., 2021). In European populations, after a period of rapid increases in body height during the second half of the twentieth century, a marked deceleration of secular trends has been observed in recent decades. This pattern has been documented in Hungarian (Bodzsár et al., 2016), Portuguese (Costa et al., 2017), Lithuanian (Venckunas et al., 2017), Romanian (Pop et al., 2021), and Swiss populations (Eichelberger et al., 2024). At the same time, numerous studies indicate that the rate of body mass increase exceeds that of height, resulting in a systematic rise in BMI values (Ates & Kaki, 2025; Negasheva et al., 2024; Topçu et al., 2017; Zhang et al., 2019). This phenomenon highlights the increasingly complex nature of contemporary secular trends and the rising importance of environmental factors associated with excessive weight gain.

In addition to biological and nutritional determinants, increasing attention has been given to the role of broader socioeconomic, environmental, and sociological factors in shaping human growth (GBD 2023 Child Growth Failure Collaborators 2026; Mekonnen et al., 2021; Tang et al., 2024). Body height is now widely recognized not only as a marker of individual health status but also as a sensitive indicator of social conditions, including family resources, social inequality, access to healthcare, and environmental quality (Mekonnen et al., 2021; Tang et al., 2024). This perspective is consistent with the concept of socio-endocrine regulation of growth, which suggests that growth processes may be influenced by social interactions and hierarchical structures within populations (Hermanussen et al., 2022).

Secular processes in Poland have been systematically documented since the 1960s. Classic studies demonstrated considerable socio-economic variation in the tempo of somatic development (Bielicki et al., 1997; Bielicki & Welon, 1982), while more recent analyses have shown a gradual reduction of these disparities (Dobosz, 2012; Przewęda & Dobosz 2005). Despite this overall convergence, contemporary trends exhibit clear spatial differentiation. Large urban centers continue to show positive, albeit increasingly moderate, increases in body height (Charzewska et al., 2004; Krawczyński et al., 2003; Kryst et al., 2022), whereas populations residing in less

urbanized areas display weaker secular dynamics (Asienkiewicz & Tatarczuk, 2018; Nowicki 2000).

Eastern Poland remains one of the least economically developed regions of the European Union. According to European Commission data (2023), the gross domestic product per capita, expressed in purchasing power standards (PPS), is slightly above 50% of the EU average. Persistent socio-economic constraints are reflected in the tempo and structure of physical development among children and adolescents. Studies show that rural populations in this region have lower mean body height and mass and slower secular changes compared with other parts of the country (Saczuk, 2018; Wilczewski, 2013). The most recent analyses covering the period 1986–2021 further indicate increases in body mass without proportional gains in height, resulting in elevated risks of overweight and obesity among adolescents living in rural areas (Saczuk & Wasiluk, 2014; Wasiluk & Saczuk, 2025).

In light of these findings, it is justified to examine long-term changes in body height, body mass, and BMI among boys residing in rural areas of eastern Poland between 1986 and 2021.

Materials and methods

Sections below describe the subjects and methods of this study that were also recently reported for the girls in this cohort (Wasiluk & Saczuk, 2026).

Study area and measurement procedures

The study was conducted in rural areas of eastern Poland, which in 1986 included the former Suwałki, Białystok, Biała Podlaska, Chełm, Zamość, Przemysł, and Krosno provinces. Follow-

ing the administrative reform of 1999, these areas became part of the Podlaskie, Lubelskie, and Podkarpackie provinces, and partially the Warmińsko-Mazurskie and Mazowieckie provinces. The first round of measurements was carried out in 1986 within the national programme “Problem Węzłowy 10.7.”. At this stage, schools were selected randomly based on regional education authority registers. In 1996, 2006, 2016, and 2021, measurements were conducted in the same schools, ensuring high temporal comparability of the data. Subsequent stages of data collection were implemented as part of statutory research projects at the Józef Piłsudski University of Physical Education in Warsaw (projects D.S. 49 and D.S. 203). Additionally, the 2021 dataset included measurements of boys participating in the nationwide programme “Aktywny powrót do szkoły – WF z AWF”. In each survey wave, all available children aged 7–15 years attending the selected schools were invited to participate. Inclusion criteria comprised residence in rural areas and school attendance at the time of measurement.

Study population

A total of 14,685 boys aged 7–15 years living in rural areas of eastern Poland were included in the analysis. This number also comprised 3,598 boys examined in 2021 within the “WF z AWF” programme. The study had a cross-sectional design, and data were collected at five time points: 1986, 1996, 2006, 2016, and 2021. The detailed age distribution of the sample by calendar age and survey year is presented in Table 1. No analyses were conducted regarding potential differences in the distribution of exact ages within yearly age groups across survey years.

Table 1. Sample size of boys by chronological age and year of observation

Age	1986	1996	2006	2016	2021	Total
7	75	33	113	222	647	1090
8	93	83	483	304	1074	2037
9	113	86	434	185	963	1781
10	134	83	374	606	739	1936
11	147	103	429	698	621	1998
12	161	88	401	646	494	1790
13	173	147	368	331	473	1492
14	174	149	393	258	303	1277
15	189	158	367	285	285	1284
Total	1259	930	3362	3535	5599	14685

Ethical considerations

Informed consent was obtained from the parents or legal guardians of all participants, and participation in the study was voluntary. Ethical approval for the initial surveys (1986, 1996, and 2006) was obtained from the relevant Faculty Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw. For the later survey waves (2016 and 2021), the study protocol was approved by the Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw (SKE 01-13/2014; 30 June 2014) (see Ethics statement for further details).

Assessment of calendar age

Dates of birth were obtained from questionnaires and used to calculate decimal age to 2 decimal places. Age was determined as the difference between the measurement date and date of birth, and subsequently classified into one-year age groups using half-year intervals (e.g., 7.50–8.49 years as the 8-year-old group), in accordance with population-based anthropometric standards.

Anthropometric measurements

Anthropometric measurements were performed using standardized anthropometric procedures appropriate for each survey period (IBP, 1969; Lohman et al., 1988). Body height was measured as standard standing height (unstretched) using a GPM Model 101 anthropometer (GPM, Switzerland), accurate to 0.1 cm, and body mass was assessed using calibrated medical scales appropriate to each survey period. From 2016 onwards, a SECA 875 electronic medical scale (SECA GmbH, Germany), accurate to 0.1 kg, was used. Participants were measured barefoot, in light clothing, in the standard anatomical position, with the head oriented in the Frankfurt plane. Body mass index (BMI) was calculated as body mass (kg) divided by height squared (m^2).

BMI categorization

BMI categories of underweight, normal weight, overweight, and obesity were determined using international age- and sex-specific BMI cut-off points proposed by Cole et al. (2000; 2007). For each

participant, BMI was calculated within the relevant age category. Underweight was divided into two groups: severe underweight (combining grade I and II underweight) and mild underweight (corresponding to grade III underweight), to ensure sufficient sample sizes in the lowest-weight categories. To provide stable estimates of prevalence, analyses were conducted within three aggregated age groups: 7–9, 10–12, and 13–15 years. For each age group, the proportion of boys classified into BMI categories was calculated for each survey year. Due to the absence of individual data in 1996, which made BMI computation impossible, this year was excluded from analyses of BMI category prevalence.

Statistical analysis

For body height, body mass, and BMI, arithmetic means and standard deviations were calculated. Differences among the five survey years were assessed using one-way analysis of variance (ANOVA). Pairwise comparisons were performed with the Games–Howell post hoc test, which is appropriate for unequal sample sizes and heterogeneous variances. To assess the overall direction and magnitude of changes across the 35-year observation period, linear regression analysis was applied as a descriptive method. The regression slope (B) was used to estimate average annual changes in body height, body mass, and BMI, whereas the R^2 value assessed model fit and the proportion of variance explained by time. Differences in BMI category prevalence among survey years were evaluated with the chi-square (χ^2) test. Statistical significance was set at $p \leq 0.05$. All analyses were performed in Statistica 13.0 (StatSoft, Kraków, Poland).

Results

One-way analysis of variance revealed significant differences in body height across survey years in all analyzed age groups ($p \leq 0.05$), as presented in Table 2. The observed changes in mean body height are illustrated in Figure 1. In the total population, between 1986 and 2021, mean body height increased by 7.85 cm, with the greatest 35-year gains observed in 13-year-olds (+10.62 cm), 9-year-olds (+8.77 cm), and 14-year-olds (+8.76 cm). The smallest changes were recorded among 7-year-olds (+5.17 cm) and 8-year-olds (+6.17 cm).

The Games–Howell post hoc test showed that significant differences in height most frequently occurred between 1986 and the values recorded in 2016 and 2021, while in the older age groups significant contrasts were also observed between 1996 and later surveys. Comparisons between consecutive stages indicated that the largest increases in body height took place between 1996 and 2006, with an average difference of 2.67 cm in the total population. The most pronounced increases in this interval were recorded in 15-year-olds (+4.86 cm) and 10-year-olds (+4.52 cm). In contrast, during the most recent interval (2016–2021), clear acceleration of height increase was noted particularly among 9-year-olds (+4.64 cm) and 13-year-olds (+4.82 cm). The smallest changes between consecutive surveys occurred during the first decade, 1986–1996 (mean: 0.57 cm), with statistically significant differences observed only in 7-, 12-, and 15-year-olds.

Linear regression analysis further confirmed a significant association between survey year and body height in all age groups ($p \leq 0.05$). The regression slopes (B) indicated a systematic increase in mean values over time, averaging 0.20–0.25 cm

per year, which corresponds to approximately 1.5–2.5 cm per decade. High coefficients of determination ($R^2 = 0.82\text{--}0.96$) demonstrated a stable and consistent pattern of changes throughout the study period. These findings suggest a sustained

improvement in growth conditions in the studied population, although the relatively moderate rate of increase may indicate a gradual stabilization of secular trends, reflecting changing environmental and socioeconomic influences.

Table 2. One-way ANOVA, Games–Howell post hoc, and linear regression results for body height in rural boys from eastern Poland (1986–2021)

Age	F	p	Test post hoc Games-Howell	B	R ²
7	18.91*	<0.001	1986<2016*, 1986<2021*, 2006<2016*, 2006<2021*	0.14*	0.82
8	67.65*	<0.001	1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.19*	0.82
9	79.93*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.21*	0.85
10	55.02*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.25*	0.91
11	59.08*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.23*	0.96
12	40.63*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.22*	0.93
13	50.10*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.25*	0.89
14	41.72*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*	0.25*	0.96
15	57.45*	<0.001	1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*	0.25	0.73

Age – age in years; F – ANOVA F-value; p – significance level; B – regression coefficient; R^2 – model fit.
*Statistically significant at $p \leq 0.05$

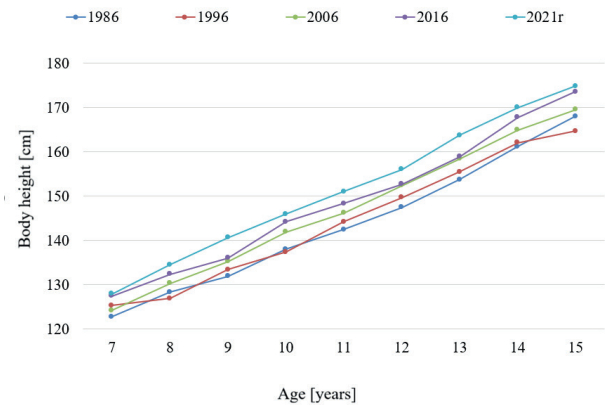


Figure 1. Mean body height of rural boys aged 7–15 years in eastern Poland across survey years

Body mass was the second somatic characteristic analysed in the present study. The results of statistical analyses are presented in Table 3, while changes in mean body mass are illustrated in Figure 2. In the total population, mean body mass increased by 5.83 kg between 1986 and 2021; however, the rate and magnitude of these changes varied across age groups. The greatest 35-year gains were observed among 14-year-olds (+8.94 kg), 15-year-olds (+8.87 kg), and 13-year-olds (+8.49 kg). In contrast, the smallest increases were recorded in 7-year-olds (+3.73 kg) and 8-year-olds (+4.33 kg).

To more precisely describe the temporal differentiation of body mass changes, the Games–Howell post hoc test was performed. This analysis showed that significant differences between survey years most frequently involved comparisons with 1986, especially in relation to 2016 and 2021. In the older age groups, significant contrasts were also observed between 1996 and later years, indicating widening disparities over time.

Comparisons between consecutive survey intervals demonstrated that the largest increase in body mass occurred between 1996 and 2006, when the mean difference for the total popula-

tion reached 2.67 kg. During this period, the greatest increases were found in 15-year-olds (+4.86 kg) and 13-year-olds (+3.65 kg). During the most recent interval, 2016–2021, the rate of change accelerated again, particularly in 14-year-olds (+3.00 kg) and boys aged 12 and 13 years (+2.71 kg and +2.72 kg, respectively). The least pronounced differences between successive survey years occurred between 1986 and 1996, when the mean increase amounted to only 0.44 kg, with statistically significant differences observed in just three age groups (7, 12, and 15 years).

The association between body mass and survey year was further confirmed by linear regression analysis. The regression slopes (B) indicated a systematic increase in body mass over time, with an average rate of 0.16–0.37 kg per year, corresponding to an increase of 1.6–3.7 kg per decade. The coefficients of determination (R^2), ranging from 0.69 to 0.91, demonstrated good model fit and a consistent pattern of changes across the study period. These findings indicate a progressive increase in body mass in the studied population and suggest a growing risk of excessive body weight among children and adolescents.

Table 3. One-way ANOVA, Games–Howell post hoc, and linear regression results for body mass in rural boys from eastern Poland (1986–2021)

Age	F	p	Test post hoc Games-Howell	B	R ²
7	28.76*	<0.001	1986<2016*, 1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.16*	0.91
8	64.18*	<0.001	1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.17*	0.78
9	69.52*	<0.001	1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2021*, 2016<2021*	0.21	0.77
10	54.63*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.25*	0.88

Table 3 (cont.)

Age	F	p	Test post hoc Games-Howell	B	R ²
11	63.95*	<0.001	1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.23	0.69
12	66.39*	<0.001	1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.27*	0.81
13	53.28*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2021*, 2016<2021*	0.30*	0.84
14	49.21*	<0.001	1986<2006*, 1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2021*, 2016<2021*	0.34*	0.86
15	72.89*	<0.001	1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.37*	0.77

Age – age in years; F – ANOVA F-value; p – significance level; B – regression coefficient; R² – model fit.
*Statistically significant at p ≤ 0.05

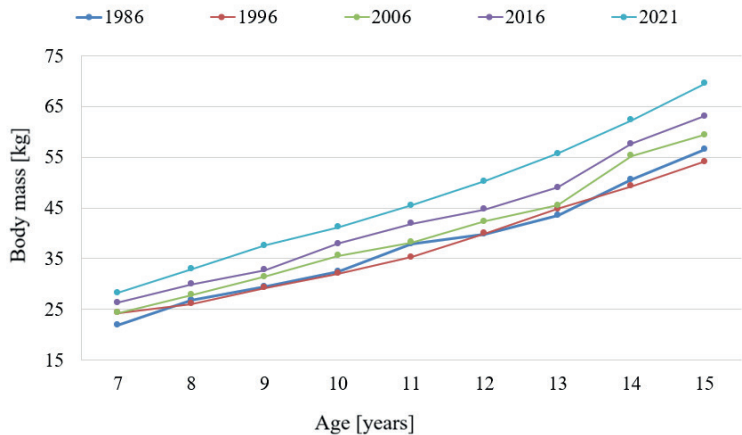


Figure 2. Mean body mass of rural boys aged 7–15 years from eastern Poland in successive survey years

The increases in body height and body mass observed across subsequent decades were accompanied by significant changes in BMI values, which reflected the overall direction of somatic development in the studied population. One-way analysis of variance confirmed that BMI differed significantly between survey years in all analyzed age groups ($p \leq 0.05$), as presented in Table 4. Changes in mean BMI values are illustrated in Figure 3.

Over the 35 years, mean BMI increased by approximately 1.21 kg/m² in the total population of boys. The largest gains were found in 14-year-olds (+1.90 kg/m²) and 15-year-olds (+1.80 kg/m²). In contrast, the smallest changes were recorded among 7-year-olds (+0.88 kg/m²) and 8-year-olds (+0.95 kg/m²), indicating that BMI increased more moderately in younger boys than in those in early adolescence.

The Games–Howell post hoc test showed that significant differences most frequently involved comparisons between 1986 and the years 2016 and 2021. In the older age groups, significant contrasts also occurred between 1996 and later survey years, suggesting that BMI changes accumulated gradually over time, with more pronounced variation among older boys.

Analysis of differences between consecutive survey intervals revealed that the most rapid increase in BMI occurred between 1996 and 2006, when the mean change in the total population reached 0.58 kg/m². The most substantial increases during this interval were observed in 14-year-olds (+1.03 kg/m²) and 15-year-olds (+0.90 kg/m²). In the most recent interval (2016–2021), BMI continued to rise, although at a slower rate, primarily among boys aged 12–15

years (increases of 0.30–0.45 kg/m²). The smallest changes were recorded between 1986 and 1996, when the mean difference amounted to only 0.09 kg/m², with statistically significant differences found in just two age groups (12 and 15 years).

The importance of time in shaping BMI values was further confirmed by linear regression models. The regression slopes (B) indicated a systematic increase in BMI ranging from 0.15 to 0.25 kg/m² per decade, whereas the coefficients of determination ($R^2 = 0.31$ – 0.74) showed that although BMI consistently increased, the rate of change varied across age groups and was more heterogeneous than for body height or body mass. These findings indicate a progressive increase in BMI in the studied population and suggest a growing risk of overweight and obesity among children and adolescents.

Table 4. One-way ANOVA, Games–Howell post hoc, and linear regression results for BMI in rural boys from eastern Poland (1986–2021)

Age	F	p	Test post hoc Games-Howell	B	R ²
7	17.35*	<0.001	1986<2016*, 1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.05*	0.87
8	35.26*	<0.001	1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.05	0.69
9	32.44*	<0.001	1986<2021*, 1996<2021*, 2006<2021*, 2016<2021*	0.05	0.64
10	22.57*	<0.001	1986<2021*, 1996<2016*, 1996<2021*, 2006<2021*, 2016<2021*	0.05	0.64
11	62.37*	<0.001	1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.08	0.67
12	38.77*	<0.001	1986<2016*, 1986<2021*, 1996<2021*, 2006<2016*, 2006<2021*, 2016<2021*	0.07	0.73
13	21.12*	<0.001	1986<2016*, 1986<2021*, 1996<2016*, 1996<2021*, 2006<2021*	0.05*	0.86
14	21.62*	<0.001	1986<2016*, 1986<2021*, 1996<2006*, 1996<2016*, 1996<2021*, 2006<2021*	0.06	0.73
15	33.17*	<0.001	1986<2021*, 1996<2016*, 1996<2021*, 2006<2021*, 2016<2021*	0.06	0.64

Age – age in years; F – ANOVA F-value; p – significance level; B – regression coefficient; R² – model fit.

*Statistically significant at $p \leq 0.05$

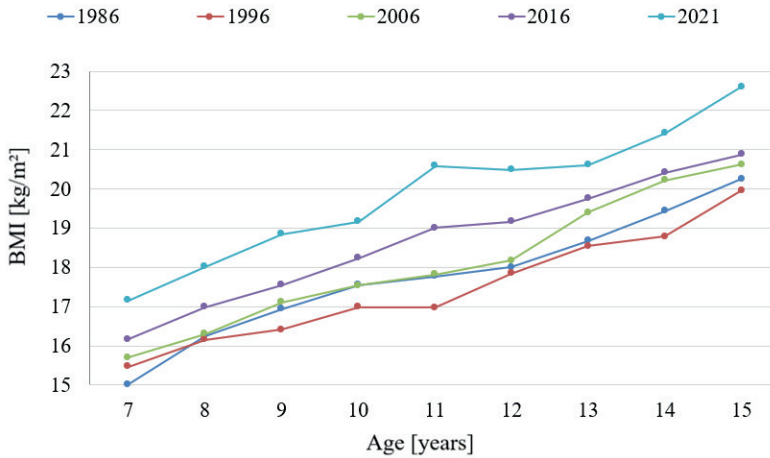


Figure 3. Mean BMI of rural boys aged 7–15 years from eastern Poland in successive survey years

To assess how the nutritional status structure evolved in the studied population, the prevalence of severe and mild underweight, normal weight, overweight, and obesity was examined across survey years, as illustrated in Figure 4. The analysis revealed statistically significant transformations in the distribution of these categories in all three age groups, as confirmed by the χ^2 test results presented in Table 5. The percentage values presented in the figure indicate a systematic increase in the proportion of boys with excessive body mass throughout the study period. The greatest increase in the combined prevalence of overweight and obesity was observed in the youngest age group (7–9 years), where it rose by 26.8% between 1986 and 2021. Comparable dynamics were noted in the 10–12-year group (+26.3%) and the 13–15-year group (+26.2%). The upward trend was consistent: both overweight and obesity increased in frequency, which was confirmed by statistically significant χ^2 results.

A particularly rapid increase in excessive body mass was recorded during the most recent interval (2016–2021). In the youngest age group, the prevalence rose by 16.7%, while in the oldest group it increased by 13.8%, indicating — as supported by the χ^2 test — a marked acceleration of this trend.

Changes in underweight were considerably more modest, as reflected by both the percentage values shown in the figure and the lower number of statistically significant differences in χ^2 tests. Among boys aged 7–9 years, the prevalence of underweight decreased by 2.2% over the entire study period; however, a slight increase was observed up to 2016 (+3.2%), followed by a substantial decline between 2016 and 2021 (–7.5%). In the 10–12-year group, the prevalence of underweight decreased by 4.2%, and in the 13–15-year group by 5.8%. The most pronounced reductions in underweight occurred in two intervals: 1986–2006 among 10–12-year-olds and 2016–2021 among 7–9-year-olds, both supported by sig-

nificant χ^2 differences. These findings point to a shift in the nutritional status structure of the studied population towards higher body mass categories, highlighting an emerging public health concern.

Table 5. Chi-square test results for BMI category prevalence across age groups and survey years

Age group	BMI category	1986–2006	1986–2016	1986–2021	2006–2016	2006–2021	2016–2021
7–9	Severe underweight	8.005*	13.032*	2.571	0.628	16.434*	22.719*
	Mild underweight	2.899	2.977	3.826	0.015	10.092*	9.613*
	Normal BMI	4.512*	9.720*	59.171*	1.000	12.992	4.585
	Overweight	16.054*	8.797*	146.341*	0.377	24.914*	27.821*
	Obesity	2.926	55.623*	266.387*	21.773*	99.863*	19.427*
10–12	Severe underweight	0.059	15.736*	2.463	15.443*	1.706	21.322*
	Mild underweight	7.572*	8.506*	19.546*	0.142	4.080*	2.499
	Normal BMI	1.927	34.311*	43.013*	19.043*	26.592*	1.036
	Overweight	53.139*	214.770*	209.349*	54.071*	56.833*	0.296
	Obesity	0.139	37.093*	180.306*	28.759*	148.910*	45.545*
13–15	Severe underweight	1.261	0.007	1.604	0.688	0.257	1.166
	Mild underweight	37.164*	33.514*	21.654*	3.852*	0.370	1.326
	Normal BMI	1.452	1.716	22.971*	0.257	15.591*	7.717
	Overweight	99.947*	65.307*	182.738*	1.057	35.390*	14.199*
	Obesity	0.170	15.345*	95.278*	12.681*	85.720*	17.141*

*Statistically significant at $p \leq 0.05$

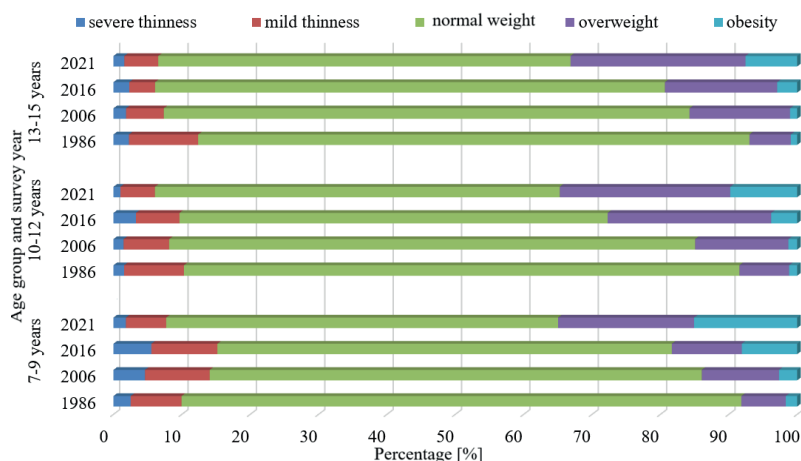


Figure 4. Changes in the prevalence of severe underweight, mild underweight, normal BMI, overweight, and obesity among boys across survey years (1986–2021)

Discussion

The results of this 35-year study of rural boys from eastern Poland confirm that secular processes in this population remain active and that their dynamics are closely linked to socio-economic transformations occurring in the region. Over the analyzed period, systematic increases in both body height and body mass were observed, although the rate of change varied across decades. The years 1986–1996 were characterized by relatively small increases, which may reflect the difficult economic conditions of the late 1980s and early 1990s, including inflationary crisis, declining household income, and the dissolution of state agricultural enterprises. Limited material and nutritional resources during this period likely constrained growth potential, which is consistent with the modest somatic changes observed.

A marked acceleration in growth occurred between 1996 and 2006, when improvements in living standards, infrastructure development, and the inflow of pre-accession and EU funds created more favorable conditions for child development in rural areas. This pattern corresponds to the mechanism of catch-up growth commonly described in rural populations, in which improved environmental conditions lead to accelerated growth following earlier constraints. These findings align with observations by Bartkowiak et al., (2022), who reported stable increases in somatic traits and a growing prevalence of overweight among rural youth in Poland between 1986 and 2016.

Particularly concerning is the pronounced increase in excessive body mass in recent years. Between 2016 and 2021, BMI values and the prevalence of over-

weight and obesity rose sharply. Although BMI is widely used as an indicator of nutritional status, it does not account for body composition or maturation status, which may limit its precision in pediatric populations; however, this does not alter the overall pattern of the observed trends. This pattern may have multiple determinants. On the one hand, continued improvements in the economic situation of rural households—supported, for example, by the “Rodzina 500+” child benefit programme (Dz. U. (Journal of Laws of the Republic of Poland) 2023, item 1565) – may have enhanced access to calorie-dense foods in economically disadvantaged regions. While the programme improved economic conditions, it may also have indirectly contributed to increased energy intake, highlighting the complex relationship between socio-economic improvement and health outcomes. On the other hand, COVID-19-related restrictions, including school closures, reduced access to sports facilities, and substantial decreases in children’s physical activity (Dz. U. 2021, item 2069; Dz. U. 2022, item 64), likely contributed to this trend. This effect may have been further intensified by increased sedentary behaviors, including prolonged screen time, observed among children during lockdown periods. Importantly, this effect may reflect not only short-term pandemic-related changes but also a broader, long-term decline in habitual physical activity observed in children and adolescents, which is considered one of the key drivers of increasing body mass and BMI in contemporary populations. Although the present study did not analyze direct economic indicators or correlations, these interpretations are consistent with patterns reported in international research.

The changes observed among rural boys in Poland reflect broader global trends. Studies conducted in China, India, and Mexico over recent decades have shown that rural populations are particularly responsive to modernization and improvements in living conditions. Li et al., (2023) demonstrated that somatic growth among rural Chinese children was strongly associated with improved infrastructure, greater access to education, and rising living standards. More recent analyses (Li et al., 2024) emphasize that although urban–rural disparities persist, rural populations exhibit the greatest sensitivity to socio-economic change. Similar patterns were described by Chanchala et al., (2022) in India and by Dang et al., (2025) in China, where intensified economic development led not only to increases in body height but also to rapid rises in excessive body mass. Findings from studies conducted in other countries suggest that processes of modernization in rural populations lead not only to improvements in living conditions but also to lifestyle changes that promote increases in body mass. Similar mechanisms may also occur in the studied population, particularly in the context of differences between rural and urban areas, where lifestyle changes may result in reduced physical activity and increased availability of high-calorie foods.

In Latin America, the relationship between secular growth trends and socio-economic transformation is particularly well documented. Malina et al., (2018), analyzing a traditional community in southern Mexico, showed that secular somatic changes were associated with epidemiological transition and an increasing prevalence of overweight as living conditions improved. Research by Azcorra and colleagues (2024; 2025) in

Maya communities likewise demonstrated that market integration is a key factor amplifying secular trends — a finding that is especially relevant in the context of post-1996 rural modernization in Poland.

The literature also indicates that rural populations are highly sensitive to resource shortages. Studies from Zambia (Mitsunaga and Yamauchi 2020), Andean communities (Burris et al., 2022), and Timor-Leste (Spencer et al., 2018) clearly show that growth tempo is strongly constrained by environmental conditions, and severe shortages can lead to lasting reductions in developmental parameters. These contrasting examples highlight the degree to which rural populations respond to both improving and deteriorating living conditions.

It is also important to note that secular trends have an intergenerational dimension. Sinha et al., (2017) demonstrated that anthropometric changes are the cumulative result of favorable conditions across generations, underscoring the value of long-term research such as the present study, which spans 35 years of Poland's socio-economic transformation.

The rise in overweight and obesity in younger age groups represents a significant public health concern. Epidemiological evidence indicates that BMI trajectories established during childhood and adolescence are strong predictors of metabolic and cardiovascular risks in adulthood. The present findings therefore highlight the need for continued monitoring of rural populations in Poland and the implementation of preventive measures aimed at promoting healthy eating and physical activity from early childhood.

The strengths of this study include its long 35-year observation period, large

sample size, and high methodological consistency of measurements, all of which enhance the reliability of the assessment of secular trends. The limitations of the study are typical of cross-sectional analyses and should be considered when interpreting the findings. A key limitation is the lack of data on biological maturation, physical activity, diet, and the socio-economic characteristics of the family and school environment, which restricts the ability to identify the mechanisms underlying the observed changes, particularly in the context of the recent increase in body mass and BMI. This limitation is especially important during puberty, when differences in the tempo of maturation may substantially influence anthropometric outcomes. In addition, the cross-sectional design precludes the analysis of individual growth trajectories, which may lead to an underestimation of intra-individual variability. The absence of BMI category data for 1996 introduces a gap in the long-term analysis of nutritional status, while the lack of direct economic indicators further limits causal interpretation. Despite these limitations, they do not undermine the assessment of somatic trends, which was the principal aim of the study. At the same time, they indicate important directions for future, more complex and multidimensional research.

Conclusions

The findings of this study confirm that secular processes among rural boys in eastern Poland remain active and have undergone a gradual transformation. Body height continues to show an upward trend, whereas in recent years, a pronounced increase in body mass and BMI has become evident. This pattern

indicates a shift from classical secular trends associated with improved living conditions toward the contemporary trajectory observed in many rural populations worldwide, in which modernization is accompanied by the rising prevalence of overweight and obesity. The observed changes, particularly prominent in the youngest age groups, underscore the need for preventive initiatives aimed at shaping healthy dietary habits and physical activity. At the same time, the results highlight the importance of continued research incorporating a broader range of environmental and socio-economic factors that may influence growth conditions among rural children. From a public health perspective, the monitoring of rural populations remains a crucial element in assessing the health of children and adolescents in Poland, especially in the context of the growing burden of excessive body mass.

Author contributions

JS: Conceptualization; methodology; study design; data collection; data analysis; interpretation of results; writing—original draft; writing—review and editing; supervision; final approval of the manuscript. AW: Conceptualization; methodology; study design; data collection; data analysis; interpretation of results; writing—original draft; writing—review and editing; supervision; final approval of the manuscript.

Ethics statement

Ethical approval for the initial surveys (1986, 1996, and 2006) was obtained from the relevant Faculty Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw within

the framework of the State Key Problem 10.7 and the internal research projects D.S. 49 and D.S. 203, in accordance with the national and institutional regulations in force at that time. Formal approval reference numbers were not assigned or are no longer available in archival records. For the later survey waves (2016 and 2021), the study protocol was approved by the Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw (approval number: SKE 01-13/2014; date of approval: 30 June 2014). Informed consent was obtained from the parents or legal guardians of all participants, and participation in the study was voluntary.

Data availability statement

The datasets generated and analyzed during the current study are not publicly available due to institutional and ethical restrictions but are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no conflict of interest regarding this paper.

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Effectiveness of equations for the prediction of stature from foot measurements in the Eastern Slovak population

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Abstract

INTRODUCTION

Stature is one of the key characteristics for establishing personal identity, particularly in forensic investigations. One of the methods for its estimation is based on a mathematical correlation between foot dimensions and body height.

STUDY AIMED

The aim of this study was to evaluate the effectiveness of various regression equations based on foot measurements for stature estimation in the Eastern Slovak population and to develop new population-specific equations.

MATERIALS AND METHODS

A total of 200 individuals (100 males and 100 females) aged over 18 years from Eastern Slovakia were analysed. Stature, foot length, and foot breadth were measured using standard anthropometric methods. Six previously published regression equations were tested and compared with newly derived models.

RESULTS

Our findings confirmed the presence of statistically significant sexual dimorphism in measured foot dimensions. Bilateral asymmetry was confirmed for foot breadth but not for foot length. A strong, positive, statistically significant relationship was found between foot length and stature, particularly in females. The accuracy of stature estimation varied depending on the applied regression approach, while newly developed models demonstrated improved predictive performance.



Original article

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CONCLUSION

Foot dimensions, especially foot length, represent reliable predictors of stature. The results demonstrated that regression equations derived from other populations do not provide uniformly accurate stature estimates, highlighting the need to develop population-specific regression models to ensure reliable forensic stature estimation.

KEYWORDS: anthropometry, correlation, estimation, foot morphology, regression equation

Introduction

The human foot reflects an individual's functional characteristics. In forensic investigation, foot measurements and footprints can provide valuable information for personal identification, such as estimating stature, body weight and build (e.g. symmetry), and potential insights into motor behaviour. These characteristics enable the identification or exclusion of an individual (Porada & Straus, 2018). Stature is an important anthropometric measurement that varies across different human groups due to genetic, environmental, nutritional, hormonal, and socioeconomic factors (Mittal et al., 2021). Prior research confirmed a strong relationship between foot measurements and stature, and that foot dimensions are thus a reliable predictor of stature (García-Mora et al., 2025; Karmalkar & Nikam, 2021). Foot length and breadth have been the major measurements used for stature predictions (e.g., Kanchan et al., 2010; Uhrová et al., 2015).

Numerous researchers have proposed regression equations for predicting stature from foot dimensions. However, due to variability in body height across populations, it is necessary to use population-specific equations for different demographic groups. Estimates of stature based on foot measurements or footprints in the Slovak population have been performed in previous studies. The study by Titlbach et al. (1971) was the first regression equation developed for the pop-

ulation of Czechoslovakia, in which stature was estimated from footprints. Later, focusing exclusively on the Slovak population, the study by Uhrová et al. (2015) estimated stature from foot dimensions in young individuals (students).

Our research aimed to assess the effectiveness of regression equations for the Slovak population, as well as equations for other European populations that are anthropometrically and geographically relatively close to the Slovak population. Our study determines which regression models developed in similar European populations can be reliably applied to the eastern Slovak population.

Material and methods

Subjects

All anthropological procedures followed the ethics protocol approved at the University of Prešov (No. ECUP-022023PO) and were taken in accordance with the 1964 Helsinki Declaration and its later amendments. The current study was conducted using 200 participants (100 males and 100 females) from Eastern Slovakia. All participants were born and raised in Eastern Slovakia and had long-term residence there. The sample can be considered representative of the adult Eastern Slovak population and was of Caucasian ethnicity. Subjects with any skeletal and pathological changes that affected the foot parameters and bipedalism were excluded. Individuals with any endocrine abnormalities (e.g. gigantism, achondroplasia)

were also excluded. The age range for the sample was 18 to 58 years. Informed consent was sought from all participants.

Measurements

Stature was measured using an anthropometer. Participants stood barefoot against a wall to ensure a vertical posture, with the measurement taken as the vertical distance from the floor to the vertex. The bony landmarks of acropodian, pternion, metatarsal tibiale, and metatarsal fibulare were identified in each subject for measurements. In Figure 1, these landmarks are represented as the points of tangency between the measurement lines and the outline of the foot silhouette.

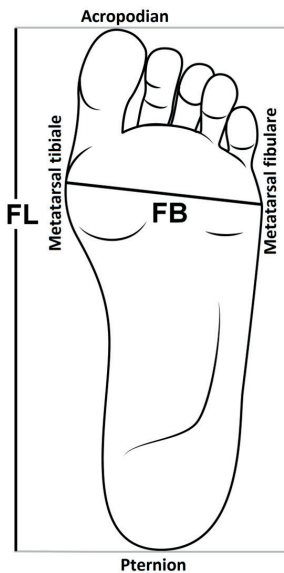


Figure 1. Anthropometric points and their distances for measurements of the foot (FL – foot length; FB – foot breadth)

The foot breadth (FB) was measured as the distance between the distal anterior epiphysis of the first metatarsal – the most prominent point on the medial side of the

foot (metatarsal tibiale) – and the distal anterior epiphysis of the fifth metatarsal, the most prominent point on the lateral side (metatarsal fibulare). The distance between the acropodian and the pternion was FL. The acropodian refers to the most anteriorly projecting point on the pad of the first or second toe, while the pternion denotes the most posteriorly projecting point of the heel (Kanchan et al., 2010). During measurement, ensuring a flat surface and even weight distribution was crucial for accuracy. Following Vallois (1965), these measurements (in cm) were taken for each foot using a digital caliper. A single trained anthropologist performed all measurements, and each measurement was conducted twice. This procedure allowed us to assess intra-observer reliability, ensuring consistency and minimizing measurement error.

Statistical analysis

Statistical analysis was conducted using SPSS statistical software (version 30). Descriptive analysis, including mean, standard deviation, minimum, maximum, was undertaken first. Data normality was evaluated using the Kolmogorov-Smirnov test. Differences between left and right foot measurements were tested using a paired t-test, while male and female comparisons were undertaken using an independent samples t-test. Pearson correlations were run to check for relationships between stature and foot measurements. Multiple linear regressions were run to calculate our own equations for stature estimation from foot dimensions.

We followed six equations to estimate the effectiveness of stature calculation (S) from foot dimensions:

1. Feix (1965): $S = 7 \text{ FL}$
2. Titlbach et al. (1971): $S = 3.1 \text{ FL} + 4 \text{ FB} + 53$

- 3. Straus (2001): $S = 3.5026 \text{ FL} + 83.883$ (for males), and $S = 2.8789 \text{ FL} + 94.038$ (for females)
- 4. Cyplík and Chojak (2010): $S = 2.4963 \text{ FL} + 113.15$ (for males) and $S = 2.9353 \text{ FL} + 96.369$ (for females)
- 5. Strnadová (2014): $S = 34.6879 + 4.00555 \text{ FL} + 4.24845 \text{ FB}$
- 6. Uhrová et al. (2015): $S = 84.74 - 0.36 \text{ FB} + 3.75 \text{ FL}$ (for males, for right side), $S = 87.75 - 0.46 \text{ FB} + 3.68 \text{ FL}$ (for males, for left side), $S = 66.89 + 1.98 \text{ FB} + 3.42 \text{ FL}$ (for females, for right side), and $S = 68.46 + 1.83 \text{ FB} + 3.42 \text{ FL}$ (for females, for left side)

To evaluate the effectiveness of regression equations for stature estimation in our sample, actual stature and estimated stature in each equation and foot side (right and left), separately for males,

females, and the total sample, was tested using a paired t-test. Equations that provided statistically non-significant differences between estimated and actual stature showed good predictive accuracy.

Results

The descriptive statistics for each measured dimension, as well as the t-test results for stature and foot dimensions, are summarised in Table 1. Among the 200 participants, the mean age ($\pm$ standard deviation, SD) was 31.94 ± 10.19 years for Slovak males and 30.56 ± 9.12 years for Slovak females. The mean values of all measurements were significantly higher in males than in females. The mean stature ($\pm$ SD) was 181.04 ± 6.07 cm in males and 167.16 ± 5.48 cm in females.

Table 1. Descriptive statistics for anthropometric measurements of the Slovak sample and statistical comparison of males and females

Parameters		Age (years)	Stature (cm)	R-FL (cm)	L-FL (cm)	R-FB (cm)	L-FB (cm)
Entire sample (n=200)	min	18	150.9	21.6	21.8	7.8	7
	max	58	196.7	29.3	29.4	12.2	12.1
	Mean	31.25	174.10	25.25	25.24	9.45	9.13
	$\pm$ SD	± 9.67	± 9.04	± 1.65	± 1.67	± 0.76	± 0.75
Males (n=100)	min	18	163.5	24	23.3	8	8
	max	58	196.7	29.3	29.4	12.2	12.1
	Mean	31.94	181.04	26.47	26.50	9.83	9.51
	$\pm$ SD	± 10.19	± 6.07	± 1.11	± 1.16	± 0.66	± 0.67
Females (n=100)	min	18	150.9	21.6	21.8	7.8	7
	max	54	185.3	27.4	28	10.7	10.3
	Mean	30.56	167.16	24.02	23.98	9.06	8.74
	$\pm$ SD	± 9.12	± 5.48	± 1.11	± 1.03	± 0.64	± 0.63
p-value		0.3296	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***

FL – Foot Length; FB – Foot Breadth; L – left, R – right, n – number, SD – standard deviation, ***statistically significant $p \leq 0.001$

The differences between measurements of the left and right foot are shown in Table 2. Bilateral asymmetry was not confirmed in foot length. There was a non-sig-

nificant bilateral difference in mean foot length for both sexes. However, a statistically significant difference was noted between the left and right means of the foot

breadth. Foot breadths were significantly larger on the right than on the left side.

Table 3 shows Pearson's correlation coefficients for actual stature and foot measurements. A stronger positive correlation with actual stature was found for the mean left and right foot lengths rather than breadth parameters. Foot length measurements were in a statistically significant ($p < 0.01$) relationship with stature in all studied groups. Foot breadth was in a statistically significant correlation with stature only in females. Stature and left foot length had the high-

est correlation coefficient of $r = 0.74$ in females and $r = 0.51$ in males.

Multiple regression equations for estimating stature from foot measurements, considering sex and foot side, developed and tested on the study sample are shown in Table 4. In both sexes, regression equations based on measurements from the left foot showed slightly better predictive accuracy than those based on the right foot. While the equations for males demonstrated only a moderate correlation, the equations for females showed stronger correlations and a lower error of estimate.

Table 2. Comparisons of the dimensions of the right and left foot

	Parameters	Mean		p-value
		Right (cm)	Left (cm)	
Entire sample	FL	25.25	25.24	0.489
(n=200)	FB	9.45	9.13	< 0.001***
Males	FL	26.47	26.50	0.847
(n=100)	FB	9.83	9.51	< 0.001***
Females	FL	24.02	23.98	0.792
(n=100)	FB	9.06	8.74	< 0.001***

FL – Foot Length; FB – Foot Breadth; n – number; ***statistically significant $p \leq 0.001$

Table 3. Correlation between actual stature and dimension of the foot

	r	
	Males	Females
Right Foot Length	0.44***	0.72 ***
Left Foot Length	0.51***	0.74***
Right Foot Breadth	-0.03 ^{ns}	0.42***
Left Foot Breadth	0.03 ^{ns}	0.43***

ns – statistically not significant; r – Pearson's correlation coefficient; ***statistically significant $p \leq 0.001$

Table 4. Multiple regression equations for stature estimation (cm) from foot dimensions according to sex, developed based on the study sample

Males				Females			
Regression equation	r	R ²	S.E.E (cm)	Regression equations	r	R ²	SEE (cm)
$S = 124.74 + 2.70RFL - 1.55RFB$	0.475	0.225	5.400	$S = 80.34 + 3.49RFL + 0.32RFB$	0.729	0.531	3.791
$S = 115.10 + 2.86LFL - 1.03LFB$	0.527	0.278	5.212	$S = 72.13 + 4.19LFL - 0.63LFB$	0.745	0.555	3.696

RFL – Right Foot Length; RFB – Right Foot Breadth; LFL – Left Foot Length; LFB – Left Foot Breadth; S – Stature, R² – Coefficient of determination, SEE – Standard Error of Estimate

The linear regression formulae developed in previous studies to estimate stature from foot dimensions were applied to our sample (Table 5). A statistical comparison of differences between actual stature and estimated stature from foot dimensions using the paired t-test in males showed that the most effective regression equation was by Uhrová et al. (2015). In addition, the equation by Strnadová (2014) also showed statistically non-significant differences between estimated and actual stature, particularly for the left foot, indicating good predictive accuracy (Table 6). In the female group, the results revealed statistically non-significant differences between actual stature and estimated stature for the equations

proposed by Feix (1965), Cyplík and Chojak (2010), Uhrová et al. (2015) for both feet, and Strnadová (2014) for the left foot, which indicates the reliability of these models. The equation by Uhrová et al. (2015) provided the most accurate stature estimation from right-foot dimensions. In contrast, the equation proposed by Cyplík and Chojak (2010) showed the highest accuracy for stature estimation based on left-foot dimensions (Table 7). For the entire sample, the statistical comparison of actual stature and estimated stature from foot measurements showed that the regression equation by Uhrová et al. (2015) was the most effective for predicting stature regardless of foot laterality (Table 8).

Table 5. Estimated stature (in cm) from foot measurements using published regression equations, applied to the study sample (mean ± SD)

Equations	Entire sample (n=200)		Males (n=100)		Females (n=100)	
	Mean±SD		Mean±SD		Mean±SD	
	Right Foot	Left Foot	Right Foot	Left Foot	Right Foot	Left Foot
Feix (1965)	176.76 ± 11.56	176.73 ± 11.7	185.32 ± 7.77	185.54 ± 8.12	168.2 ± 7.78	167.92 ± 7.23
Titlbach et al. (1971)	169.08 ± 7.38	167.83 ± 7.46	174.41 ± 4.90	173.22 ± 5.02	163.75 ± 5.32	162.36 ± 5.19
Straus (2001)	169.91 ± 7.6	169.91 ± 7.7	176.61 ± 3.89	176.72 ± 4.07	163.22 ± 3.2	163.10 ± 2.97
Cyplík and Chojak (2010)	173.07 ± 6.88	173.05 ± 6.94	179.24 ± 2.77	179.31 ± 2.90	165.85 ± 3.75	166.78 ± 3.03
Strnadová (2014)	175.98 ± 8.97	174.61 ± 9.06	182.51 ± 5.90	181.27 ± 6.06	169.45 ± 6.39	167.94 ± 6.20
Uhrová et al. (2015)	173.74 ± 8.03	173.77 ± 8.4	180.47 ± 4.10	180.91 ± 4.2	167.02 ± 4.63	166.51 ± 4.36

n – number, SD – Standard Deviation

Table 6. Statistical comparison of differences between the actual stature and estimated stature from foot dimension in males, using published equations applied to the study sample

	Right Foot					Left Foot				
	Average of differences	SD _d	t	Normality P-value	P-value	Average of differences	SD _d	t	Normality P-value	P-value
Feix (1965)	4.27	7.42	5.76	0.023	≤ 0.001***	4.49	7.21	6.23	0.00075	≤ 0.001***
Titlbach et al. (1971)	-6.64	6.58	-10.08	0.00062	≤ 0.001***	-7.82	6.21	-12.60	0.011	≤ 0.001***
Straus (2001)	-4.43	5.56	-7.97	0.0027	≤ 0.001***	-4.33	5.29	-8.18	0.0029	≤ 0.001***
Cyplík and Chojak (2010)	-1.81	5.44	-3.33	0.0025	≤ 0.001***	-1.73	5.29	-3.32	0.009	≤ 0.001***
Strnadová (2014)	1.47	6.98	2.11	0.0004	0.038	0.23	6.59	0.35	0.0081	0.728
Uhrová et al. (2015)	-0.57	5.57	-1.02	0.004	0.311	-0.133	5.28	-0.25	0.0032	0.802

SD_d – Standard Deviation of differences; t – test statistic of the paired t-test; Normality P-value – shape of distribution; P-value – difference between values; *** statistically significant p≤ 0.001

Table 7. Statistical comparison of differences between the actual stature and estimated stature from foot dimension in females, using published equations applied to the study sample

	Right Foot					Left Foot				
	Average of differences	SD _d	t	Normality P-value	P-value	Average of differences	SD _d	t	Normality P-value	P-value
Feix (1965)	1.037	5.33	1.94	0.592	0.0547	0.76	4.84	1.56	0.545	0.1212
Titlbach et al. (1971)	-3.41	4.33	-7.88	0.1654	≤ 0.001***	-4.81	4.35	-11.04	0.085	≤ 0.001***
Straus (2001)	-3.95	3.84	-10.29	0.678	≤ 0.001***	-4.07	3.83	-10.61	0.0527	≤ 0.001***
Cyplík and Chojak (2010)	-0.26	3.83	-0.69	0.7282	0.4909	-0.38	3.82	-1	0.0557	0.3192
Strnadová (2014)	2.29	4.73	4.83	0.5984	≤ 0.001***	0.78	4.7	1.65	0.3415	0.102
Uhrová et al. (2015)	-0.15	3.9	-0.38	0.3898	0.708	-0.65	3.85	-1.7	0.1173	0.0923

SD_d – Standard Deviation of differences; t – test statistic of the paired t-test; Normality P-value – shape of distribution; P-value – difference between values; *** statistically significant p≤ 0.001

Table 8. Statistical comparison of differences between the actual stature and estimated stature from foot dimension in the entire sample, using published equations applied to the study sample

	Right Foot				Left Foot					
	Average of differences	SD _d	t	Normality P-value	P-value	Average of differences	SD _d	t	Normality P-value	P-value
Feix (1965)	2.66	6.65	5.65	0.00099	≤ 0.001***	2.62	6.4	5.79	0.000036	≤ 0.001***
Titlbach et al. (1971)	-5.02	5.79	-12.27	0.0741	≤ 0.001***	-6.32	5.56	-16.07	0.6586	≤ 0.001***
Straus (2001)	-4.19	4.77	-12.42	0.00137	≤ 0.001***	-4.2	4.61	-12.88	0.0019	≤ 0.001***
Cyplík Choják (2010)	-1.04	4.75	-3.08	0.0079	≤ 0.001***	-1.06	4.6	-3.24	0.01	0.00138
Štrnadová (2014)	1.88	5.96	4.45	0.0036	≤ 0.001***	0.5	5.72	1.24	0.0433	0.2148
Uhrová et al. (2015)	-0.36	4.8	-1.05	0.0059	0.2939	-0.4	4.62	-1.21	0.00184	0.229

SD_d – Standard Deviation of differences; t – test statistic of the paired t-test; Normality P-value – shape of distribution; P-value – difference between values; ***statistically significant p≤ 0.001

Discussion

Foot measurements, footprints or shoeprints can play a key role in forensic investigations. Direct anthropometric measurements, such as foot length and foot breadth, provide accurate, population-specific data that enable forensic anthropologists to estimate stature and create a biological profile of an individual (Krishan, 2008). In cases of mass disasters or natural catastrophic events where bodies may be fragmented or partially recovered, these direct measurements are often essential for reliable victim identification and effective disaster management (Davies et al., 2014). Footprints and shoeprints at crime scenes are an important additional source of evidence. Even partial or single footprints can preserve measurable characteristics – such as length, width, and pressure patterns – that correlate with an individual's height and often provide information about their gait, weight distribution, or locomotion, which can be crucial in revealing their identity (Reel et al., 2012). Analysis of these prints allows investigators to obtain key data for identifying suspects or reconstructing events, especially when no other direct physical evidence exists (García-Mora et al., 2025). In practice, foot measurements and footprints have become the basis for creating and applying regression equations that enable the estimation of stature for individuals from a specific population (Krishan et al., 2015). The higher the number of individuals in the population included in the creation of regression equations, the greater their accuracy and applicability in real investigative situations (Hansen et al., 2022).

This study was conducted to provide anthropometric data on foot length and

breadth for adults from eastern Slovakia, adding to existing data. Our study provided data on foot dimensions and their relationship to stature across a wider age range of adults from this region. On the other hand, this study examined available regression equations for the Slovak population to estimate stature from foot dimensions or footprints and their effectiveness for a given demographic group.

Anthropometric measurements showed that Slovak males' foot measurements were significantly larger than those of females, but this was due to sex and biological factors (Ulijaszek et al., 1998). Previous studies (Krauss et al., 2008; Ozaslan et al., 2012; Romphothong & Traithepchanapai, 2019; Wunderlich & Cavanagh, 2001) demonstrated significant sex differences in all foot parameters. In our study, the mean body height ($\pm$ SD) was 181.04 ± 6.07 cm in males and 167.16 ± 5.48 cm in females, which is consistent with the statistical analysis of the mean body height of the Slovak population published by Worlddata.info (2025). A study by Hitka et al. (2018) reported average body height ($\pm$ SD) in Slovak males to be 182.1 ± 6.7 cm and in Slovak females 168.2 ± 5.9 cm. The authors predicted that the average height of Slovak males could reach the value of 184.27 cm in the year 2025. The increase in body height in a population may also influence changes in average foot measurements.

Anthropological analysis confirmed bilateral asymmetry of foot breadth, which was significantly larger on the right side across all studied groups and may indicate a higher load on the dominant foot. This result was consistent with the previous study by Kanchan et al. (2010) in the North Indian population. The study by Hemy et al. (2013) report-

ed different results, confirming that the left foot was significantly larger than the right in males in the Western Australian population. In contrast, in females, there was no significant asymmetry. The study by Sen and Ghosh (2008) showed that both adult males and females from North Bengal had significantly longer left feet. Krishan and Sharma (2007) indicated that bilateral variation was not significant for all foot measurements in both sexes in the North Indian population. A similar conclusion was noted by Saxena et al. (2023) in a research group from Uttar Pradesh, by Karaddi et al. (2013) in males from Karnataka, in India.

Sexual differences in human body characteristics and their relations are well-established and documented (Danborgno & Elukpo, 2007; Kirchengast, 2014). Our study clearly demonstrated that the length parameters showed a significantly stronger positive correlation with stature than the foot breadth in the male population. On the other hand, in females, an important relationship between stature and both foot length and foot breadth was seen. The study by Ozaslan et al. (2012) found that a stronger correlation was observed between all variables and stature in males than in females. It was in agreement with the Ozdens et al. (2005) study, which also confirmed that foot length showed a better correlation with stature than foot breadth. The same result was found in research by Kim et al. (2018). A different result was obtained by the study of Igbigbi et al. (2018), which found that the breadth parameters showed a stronger correlation with foot measurements in the Nigerian population. Different biological growth mechanisms can explain the varying strength of the correlation between stature and individual

foot dimensions. Stature is primarily influenced by epiphyseal growth of long bones, a genetically regulated process closely associated with longitudinal dimensions, such as the foot length (Jee & Baron, 2016). Foot length shows a strong and consistent correlation with stature across populations and sexes (Kim et al., 2018). In contrast, foot breadth is more influenced by periosteal expansion, mechanical loading, body weight, footwear habits, and movement behavior, leading to greater interindividual variability (Xiong et al., 2009). Foot breadth shows a weaker relationship with stature (Singh et al., 2019), especially in men, which can be attributed to sexual dimorphism, as men tend to have more robust and wider feet at comparable statures, resulting in reduced predictive value of this parameter (Luo et al., 2009; Putti et al., 2010; Singh et al., 2019). Wunderlich and Cavanagh (2001) confirmed that women's feet differ from men's in several characteristics, such as the arch, toes, the ball of the foot, and the lateral side of the foot, which are important when designing shoes.

Environmental influences such as nutrition, physical activity, habitual footwear, and secular trends change the shape and size of the foot over time, regardless of body type. Regression equations developed for one demographic group or time period may not apply accurately to another (Kouchi, 2003). Each researcher on this issue has developed population-specific regression formulas. Some take sex into account; others take laterality into account as well. Our goal was to identify the effectiveness of stature estimation equations for the Eastern Slovak population. The regression equation by Titlbach et al. (1971) was created for forensic practice at a time

when the Slovak population was part of Czechoslovakia. Although this equation was based on foot dimensions, it proved inappropriate for the current population living in Eastern Slovakia, which may be attributed to secular trends in stature across generations. Our results showed that the regression equations of Uhrová et al. (2015) were the best for estimating stature from foot dimensions for the Eastern Slovak population. Their research followed young Slovak students and used correlation and regression analysis to determine the relationships between stature and measurements of the feet and hands. Moreover, the equations of Uhrová et al. (2015) were also based on foot laterality and sexual dimorphism. Our study also used equations from Strnadová et al. (2014) for the Czech population and from Cyplík and Chojak (2010) for the Polish population, which share borders and ethnic origins with Slovakia. However, a comparison of estimated and actual stature showed that the accuracy of these equations varied depending on sex and foot laterality. In both equations, we also observed statistically significant differences between the estimated and actual stature in the analyzed groups. These findings suggest that even geographically close and ethnically similar populations may differ in anthropometric characteristics, potentially affecting the reliability of stature-estimation models.

Our results contribute to the importance of introducing an optimal population-specific regression equation for estimating stature into Slovak forensic practice, which could help analyse foot in forensic investigations. We confirm the opinion of other authors that different regression equations need to be developed for various populations and ethnic

groups (Ashizawa et al., 1997; Hisham et al., 2012; Parlak et al., 2024; Singh et al., 2019) due to different cultures and lifestyles, mechanical effects of use and wear, and physical stress affecting body morphology and height changes (Bagga, 2013). These aspects must also be kept in mind when we create an individual profile from foot dimensions. The data and equations we present might be valuable in future anthropological and forensic research, as well as genetic studies and medical practice.

Conclusion

The presented anthropometric study contributes to the existing data on foot dimensions in Slovak adults. The following key findings were observed: a statistically significant difference in foot measurements between males and females, in right and left foot breadth, and between actual stature and foot length. These findings confirmed the presence of sexual dimorphism and bilateral asymmetry in foot dimensions and predicted stronger correlations between foot dimensions and actual stature in females. The findings underline the necessity of using population-specific regression equations when estimating stature from foot dimensions in forensic contexts. Among available regression equations for stature estimation, the formulas suggested by Uhrová et al. (2015), which accounted for laterality and sex, were the most accurate in our study group. Therefore, we recommend their application and have also proposed our formulas, which should be verified in other Slovak research groups. These findings have potential for use in Slovak forensic practice, particularly for cases involving the analysis of foot.

Contributions from individual authors

E. Petrejčíková, M. Zigová, contributed to conception and design, data acquisition, drafted and critically revised the manuscript; J. Gaľová, L. Kmeťová, contributed to conception and design, data acquisition, and critically revised the manuscript; S. Kalafutová, M. Pavlíčková, contributed to design, data analysis and interpretation, and critically revised the manuscript. All authors gave their final approval and agreed to be accountable for all aspects of the work.

Ethics Statement

All anthropological procedures performed in this study were in accordance with the ethical standards of the research committee at the University of Prešov (No. ECUP-022023PO) and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Case study of an osteolytic lesion in the mandible of an individual from Danilo (Croatia)

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Abstract

OBJECTIVE

This case study presents an osteolytic lesion on the entire mandibular body in an individual from Danilo (Croatia) (17th–18th centuries AD).

MATERIALS

The individual is an estimated male, with the age of death assessed as 45–49 years.

METHODS

Macroscopic, microscopic and radiographic methods were used to evaluate the osteolytic lesion. Cone Beam Computed Tomography scans were also collected.

RESULTS

The lesion displays an irregular yet predominantly ovoid outline. Its internal structure is osteolytic with partially eroded internal septa. The radices of tooth 47 exhibit partial, mild resorption.

CONCLUSIONS

The findings indicate that we may be dealing with either an odontogenic keratocyst or ameloblastoma. Considering the age and sex of the individual, the specific location and the radiological characteristics, we suggest odontogenic keratocyst as the most likely diagnosis.

KEYWORDS: mandible, odontogenic keratocyst, ameloblastoma, Danilo



Original article

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Introduction

The majority of studies of the masticatory system in historical populations focus on dental calculus (Forshaw, 2022; MacKenzie et al., 2023), dental caries (Bertilsson et al., 2022; Moles, 2023), periodontal disease (Konig et al., 2010; Vodanović et al., 2012), and/or enamel hypoplasia (Berbesque & Doran, 2008; Towle & Irish, 2020). Large osseous lesions associated with bone remodelling are reported less frequently in the literature. These usually include radicular cysts and/or lateral periodontal cysts of inflammatory origin (Carrascal et al., 2013; Neiburger, 1977; Salama & Hilmy, 1951). In this article, we describe a case of a large mandibular lesion from the archaeological site of Danilo (Croatia). To our knowledge, this is the first report of such an extensive mandibular lesion from the Danilo site.

The remains analysed in this study originate from excavations carried out

at the Danilo–Cemetery site, located in the central Dalmatian village of Danilo in Šibenik-Knin County, Croatia. Danilo is situated approximately 10 km from the Adriatic coast, within a valley approximately 10 km long and 1.5 km wide, bordered by low ridges (Figure 1). Of particular interest are the cemeteries uncovered at the site, which span the period from the 5th/6th century AD to the early Modern Period (Brajković et al., 2013; Krnčević, 1994). According to 13th-century records, settlement in the area was sparse and organised, as it is today, into hamlets scattered along the edges of the field (Krnčević, 1994), a pattern also reflected by the multiple small medieval cemeteries identified at Danilo (Krznar et al., 2024). A central burial ground, apparently established as early as Late Antiquity, occupied the area around and to the west of St Daniel's Church both before and after the church was constructed, and part of it remains in use today.

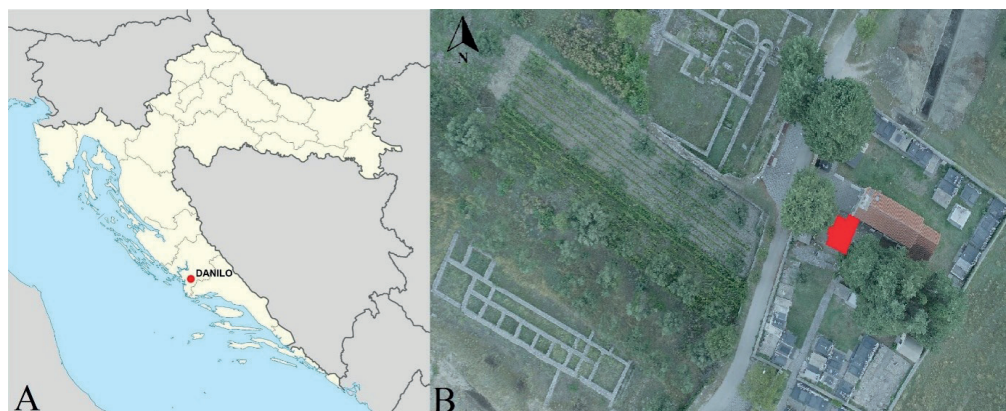


Figure 1. Location of the archaeological site: A – location of Danilo (basemap: Wikimedia Commons); B – aerial view of the cemetery and Stari Šematorij sites with the location of the excavation marked (author: K. Rabięga)

Recent research was initiated at Danilo to investigate changes in settlement patterns from the Roman period to the Middle Ages within this micro-region through remote sensing, the analysis of legacy data, archaeological survey, and excavation (Konestra et al., 2020). A small number of graves has been discovered south of the church, where the modern cemetery is located (Krnčević, 1994; Rabiega et al., 2025). The present case study focuses on Grave No. 2 (G2), which extended beyond the limits of the excavation trench, allowing only its north-western part to be investigated. The grave typology and associated finds indicate that the burials within G2 date to the 17th–18th centuries.

Material and Methods

During the 2024 excavation season, an almost complete skeleton of an adult male (G2 SJ98 U-57/U-59) exhibiting pathological changes in the mandible was excavated at Danilo (Croatia). The skeletal remains included the skull and mandible, both humeri, the left ulna, all vertebrae, ribs, the left scapula, and the right hip bone. The remains were in a good state of preservation. The material was initially examined in the field laboratory at Danilo during the excavation season, while the skull and mandible were subsequently prepared for detailed analyses in specialist laboratories in Poland.

Macroscopic, microscopic, and radiographic methods were used to evaluate the osteolytic lesion. Radiographic examinations were performed at the Department of Dental and Maxillofacial Radiology, Medical University of Warsaw. Cone Beam Computed Tomography (CBCT)

scans were acquired using a Papaya3D+ system (Genoray, Seoul, Korea). The scan parameters were as follows: 70 kVp, 7 mA, field of view (FOV) 160 × 160 × 80 mm, voxel size 0.2 mm, and voxel spacing 0.2 mm. The CBCT images were evaluated by a dentomaxillofacial radiologist with 14 years of experience in dental radiology.

Results

The sex of the individual was estimated using both the method proposed by Ferembach et al. (1980) and the more recent method developed by Brůžek (2002), which involves three stages: scoring the pelvic traits, assessing their morphology, and determining sex based on five pelvic features. Sex was also assessed through the morphological evaluation of the skull following the standards of Buikstra and Ubelaker (1994).

Age-at-death was estimated based on morphological changes to the auricular surface of the ilium and the pubic symphysis (Brooks & Suchey, 1990; Buikstra & Ubelaker, 1994; White & Folkens, 2000). According to these criteria, the individual was identified as a male aged between 45 and 49 years at death.

The following teeth are preserved in the mandible: the left canine (33), the left first (34) and second (35) premolars, and the right second molar (47). The alveoli of the remaining anterior teeth remain open, whereas those of the posterior teeth on the left side are completely obliterated. On the right side, all teeth are missing except for tooth 47, as the entire right mandibular body is affected by an extensive osteolytic lesion. The crown of tooth 47 is severely destroyed and appears to have been “burst” from within (Figure 2).



Figure 2. Mandible of individual G2 SJ98 U-57/U-59 with an osteolytic lesion on the right side

In the maxillary dental arch, only the teeth on the right side are preserved: the first (14) and second (15) premolars, and the first (16) and second (17) molars. On the left side, only the second incisor (22) and canine (23) remain. Some of the alveoli on the left side are completely obliterated. The posterior teeth on the right-side exhibit extensive dental calculus deposits on both the buccal and palatal surfaces.

The mandible exhibits a unilateral lesion involving the entire right body of the mandible at the level of the molars, extending into the gonial region and corresponding to the edentulous alveolar segment formerly occupied by teeth 43–46.

The lesion has an irregular but predominantly ovoid outline. Its internal structure is osteolytic, with partially eroded internal septa. The lesion measures approximately $41.4 \times 22.3 \times 22.1$ mm in the mesiodistal, craniocaudal, and buccolingual dimensions, respectively. It perforates the cortical bone, producing focal discontinuities along the inferior border, buccal cortex, and alveolar crest of the mandible, while the remaining margins are well defined and surrounded by a rim of reactive osteosclerosis. The roots of tooth 47 project into the posterior aspect of the lesion and exhibit mild, partial resorption. Owing to its mass effect, the lesion displaces the inferior alveolar canal superiorly and buccally. The mental foramen is displaced posteriorly relative to the contralateral side and opens at the level corresponding to the anatomical positions of the missing teeth 45 and 46.

Radiographic assessment also revealed a discrete linear radiolucency consistent with a fracture line traversing the lesion. No reparative osseous changes, such as periosteal callus formation, cortical bridging, or bone remodelling, were identified. Collectively, these findings favour a post-mortem defect rather than an antemortem traumatic fracture. No additional pathological changes affecting the mandible were observed (Figures 3–4).

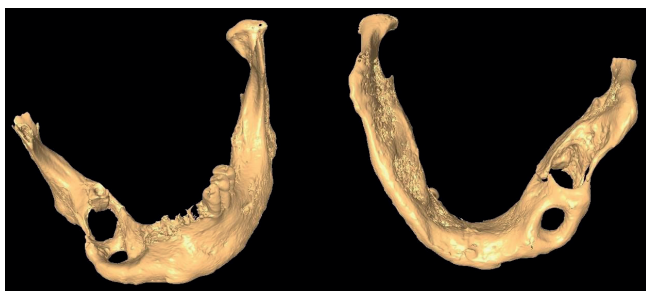


Figure 3. Volume rendering reconstruction of the mandible. To the left is shown anterior view, while on the right the view of the mandible is partly inferior and posterior

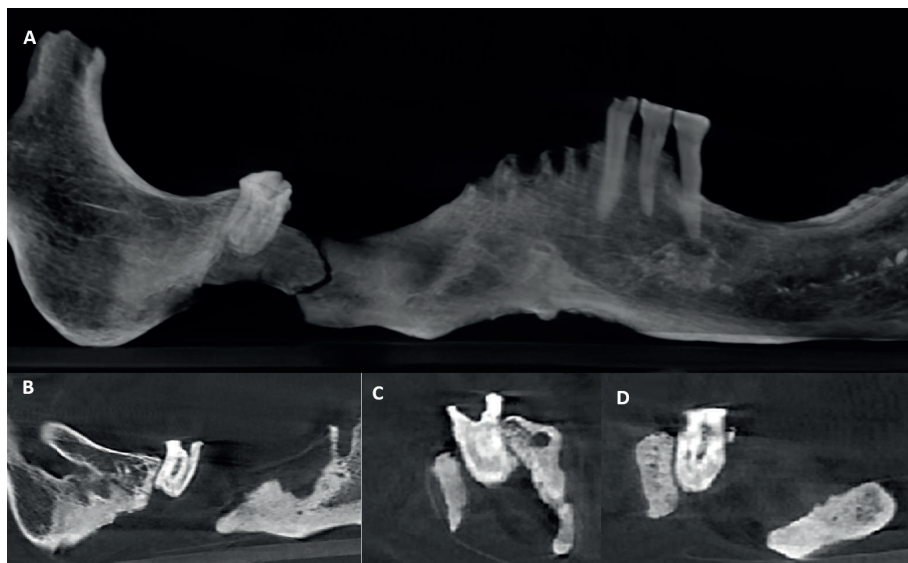


Figure 4. Radiographic image of the osteolytic lesion in three projections: A) panoramic reconstruction, B) oblique slice, C) coronal slice, D) sagittal slice

Discussion

As is often the case with archaeological material, a definitive differential diagnosis is not possible. The principal diagnostic considerations are odontogenic keratocyst and ameloblastoma. Less likely diagnoses include a radicular cyst (Deshmukh et al., 2014), central giant cell granuloma (Butel et al., 2018), adenomatoid odontogenic tumour (More et al., 2013), ameloblastic fibroma (de Castro et al., 2014; Vij & Vij, 2013), and calcifying epithelial odontogenic tumour (Singh et al., 2011).

Radicular cysts rarely enlarge to the extent observed in the present case (Deshmukh et al., 2014). A diagnosis of central giant cell granuloma is considered unlikely, as approximately 75% of cases occur in children and young adults, with the highest incidence during the first three decades of life (Butel

et al., 2018). Adenomatoid odontogenic tumour occurs predominantly during the second and third decades of life, exhibits a marked female predilection (approximately 2:1), and most commonly arises in the anterior maxilla, where it is typically associated with an unerupted canine (More et al., 2013). It is estimated that adenomatoid odontogenic tumours account for 2.2% to 8.6% of all odontogenic tumours. Ameloblastic fibroma is a rare (<2%) benign mixed odontogenic tumour composed of ameloblast-like epithelial strands embedded within a dental papilla-like mesenchyme. Most cases occur during the first two decades of life (mean age approximately 15 years), without a clear sex predilection, and show a marked preference for the posterior mandible, frequently surrounding an impacted or unerupted tooth (de Castro et al., 2014; Vij & Vij, 2013). Calcifying epithelial odontogenic tumour (CEOT, or

Pindborg tumour) is a rare benign epithelial odontogenic neoplasm, accounting for approximately 0.4–3% of all odontogenic tumours (Singh et al., 2011).

Odontogenic keratocysts most frequently arise within the mandibular body and ramus (Borghesi et al., 2018). The lesion is most commonly detected in patients aged 20–50 years and shows a male-to-female predilection of approximately 2:1 (Atwal et al., 2019; Bello et al., 2016). The age, sex, and lesion location in the individual from Danilo are consistent with the reported epidemiological data for this condition. Clinically, these lesions may remain asymptomatic for prolonged periods and are therefore most often identified on radiographic examination.

Radiographically, odontogenic keratocysts present as solitary, round to ovoid radiolucent osteolytic lesions with well-defined margins and a surrounding sclerotic border (Borghesi et al., 2018). In larger lesions, the peripheral sclerotic rim may become attenuated or may be entirely absent (Koppula et al., 2015). Odontogenic keratocysts typically arise within the cancellous bone; however, as they enlarge, they may expand and compromise the integrity of the surrounding cortical bone. In more advanced cases, internal septations may develop, resulting in a multilocular radiographic appearance (Batra et al., 2024). Large odontogenic keratocysts may exert a mass effect, leading to displacement of adjacent teeth, deflection of the mandibular canal, and expansion of the bone. Root resorption is occasionally observed and corresponds to the radiological findings in the present individual, which demonstrate mild resorption of the roots of tooth 47.

Multiple odontogenic keratocysts are a characteristic feature of the Gorlin–Goltz

syndrome (Abdi et al., 2016). Until the 2022 revision, the World Health Organization classified odontogenic keratocysts as a benign neoplasms, a designation based primarily on the frequent identification of pathogenic PTCH1 mutations in the lesional epithelium. However, the 2022 (5th edition) update reclassified it as a developmental cystic lesion (Soluk Tekkesin & Wright, 2022; WHO, 2022).

A diagnosis of odontogenic keratocyst has been reported in only a few individuals from historical periods, including a case from Egypt dated to approximately 2800 BC (Salama & Hilmy, 1951), a prehistoric American Indian individual (Neiburger, 1977), and a male individual from Santa Magdalena d'Empúries (Chimenos-Küstner & Agustí-Farjas, 2006). The characteristics observed in the present case are consistent with those reported for odontogenic keratocysts in the palaeopathological literature. However, the interpretation of these historical cases was based solely on radiographic and macroscopic findings, without histological confirmation. In the reported cases, particular attention was drawn to pathological changes involving the mandibular ramus. These lesions were osteolytic in nature and exhibited a multilocular appearance. No evidence of an acute inflammatory process, such as irregular bone resorption or reactive new bone formation, was observed. Instead, the lesions were considered more consistent with a benign but locally aggressive odontogenic lesion than with an abscess or post-traumatic pathology (Chimenos-Küstner & Agustí-Farjas, 2006; Neiburger, 1977; Salama & Hilmy, 1951).

Another disease entity that could explain the Danilo case is ameloblastoma. These are classified as benign odontogenic neoplasms with locally aggressive be-

haviour and represent the most common odontogenic tumours associated with impacted teeth (Soluk Tekkesin & Wright, 2022; WHO, 2022). They typically originate from the odontogenic epithelium of the dental lamina but may also arise from the epithelial lining of odontogenic keratocysts (Kumar et al., 2022).

Ameloblastomas most commonly occur in the mandible and show a higher prevalence in males than in females (Ghai, 2025; Vila et al., 2025). They are most frequently diagnosed between the second and fourth decades of life. It is estimated to account for approximately 10% of neoplasms of this type. Radiologically, ameloblastomas typically present as well-demarcated osteolytic lesions with a surrounding sclerotic margin (More et al., 2012). They may exhibit either unilocular or multilocular radiographic patterns (Ranchod et al., 2021).

Although ameloblastomas generally grow slowly, they can eventually reach considerable size and, in rare cases, produce a pronounced mass effect on adjacent structures (Lovásová et al., 2021). They are capable of causing cortical bone resorption and invading adjacent soft tissues. Root resorption of adjacent teeth is a frequent radiographic finding (Struthers & Shear, 1976). They may also displace the mandibular canal and compromise its cortical boundaries (Evangelista et al., 2021).

Only a few cases of ameloblastoma in historical populations have been described in the literature, including examples from South America (550–850 CE) (Bartelink & Wright, 2011), Italy (5th–6th century BCE) (Capasso et al., 2001), and Italy (17th–19th centuries CE) (Cilli & D'Anastasio, 2017). The most characteristic features of the lesion observed in the present case include its localisation in

the posterior mandible (angle and ramus region), marked bony expansion resulting in cortical “ballooning,” a multilocular appearance, extensive osteolysis, and thinning and remodelling of the cortical bone with partial preservation of its continuity. The well-defined lesion margins suggest a slow, chronic pathological process.

As only skeletal remains are available, assessment of the functional impact of the lesion is inherently limited. Nevertheless, it is reasonable to assume that the extensive osseous changes observed in the individual from Danilo adversely affected overall well-being and daily functioning. The destruction of the mandible was accompanied by the loss of teeth on the right side, which likely resulted in difficulties with mastication, swallowing, and possibly speech. Given the extent of the lesion, facial swelling and deformity may also have been present. Furthermore, a lesion of this size could have caused paraesthesia or hyperaesthesia within the distribution of the inferior alveolar nerve (Vincent's sign), reflecting compression or involvement of the neurovascular bundle (Otto et al., 2009).

The present study has certain limitations. First, it should be noted that the diagnosis is based solely on archaeological skeletal material. No soft tissues are preserved that could definitively confirm the diagnosis. Therefore, in the absence of histopathological examination – which is not always feasible in archaeological contexts – differentiating between ameloblastoma and certain extensive odontogenic cysts can be particularly challenging. In archaeological and historical contexts, diagnosis is usually based primarily on morphological and radiological evidence, which increases the uncertainty of interpretation

(Table 1). A second limitation is the small number of reported cases from historical populations and, consequently, the limited comparative material available for the individual from Danilo. This means that, based on the available evidence, this represents the most likely diagnosis, although alternative explanations cannot be excluded.

Table 1. Comparison of characteristics of ameloblastomas and keratocytes as identified here as two probable diagnoses

Feature	Ameloblastoma	Keratocytes
Location in the mandibular ramus	Yes	Yes
Osteolysis	Yes	Yes
Multilocular appearance	Common	May occur
Well-defined margins	Yes	Yes
Slow growth	Yes	Yes
Local aggressiveness	Yes	Yes
Root resorption	Common	May occur
Mass effect	May occur	Common

Conclusions

Studies of pathological conditions observed in archaeological material are valuable as they allow the investigation of disease patterns and abnormalities in past populations. This study describes a probable case of an odontogenic keratocyst in a male individual aged 45–49 years at death. To the best of our knowledge, this represents the first case of such extensive mandibular bone changes recorded at the examined site in Danilo (Croatia). Further research is needed at archaeological sites where similar mandibular changes are observed, to allow for meaningful comparative analysis.

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Author contributions

JT – research concept and design, conducting biological research, writing the article, final approval of the article, AK – conducting archaeological research, writing the article (archaeological section), FW – conducting archaeological research, KR – conducting archaeological research, writing the article (archaeological section), TB – conducting archaeological research, PR – radiographic examinations, critical revision of the article.

Ethics statement

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

Data availability statement

Data are available from the corresponding author upon reasonable request.

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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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The role of parental age, family dynamics, and historical adversity in craniofacial variation of pre-World War II cadets

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Abstract

OBJECTIVE

This study examined how parental age, family context, and historical stressors relate to variation in craniofacial and body dimensions among male cadets from pre-World War II Lviv.

MATERIAL AND METHODS

The sample included 365 male cadets measured in Lviv in 1938. Using Spearman correlations, Mann-Whitney U tests, and Generalized Additive Models with covariate adjustment, we tested whether parental age differences, socioeconomic factors, early-life stress, and family mortality predicted variation in fifteen anthropometric dimensions.

RESULTS

Parental ages were strongly correlated, consistent with age-assortative mating. Larger parental age differences were associated with smaller jaw width, shorter head length, and variation in craniofacial shape, whereas advancing paternal age was associated with smaller jaw width and variation in overall craniofacial size. Maternal age showed only weak, non-significant trends. Higher parental occupational status predicted greater body height and weight. Variation in body height, nasal height, and overall craniofacial size was also related to sibling mortality. Cohorts corresponding to the periods of World War I and the Spanish flu exhibited smaller jaw width and lower body mass. Despite substantial parental mortality, no significant anthropometric differences were observed between individuals with known and unknown parental-age data.

CONCLUSIONS

Associations between parental age variables and offspring anthropometry were generally weak and limited to specific craniofacial traits. Future research using larger and more diverse samples is needed to determine whether the observed patterns reflect general biological processes or are specific to this cohort.

KEYWORDS: parental age difference, anthropometry, early-life stress



Original article

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Introduction

Parental age at reproduction is a well-established determinant of offspring development and health, shaped by both biological and social factors (Liu et al., 2011; Zhang et al., 2022). Advanced paternal age is associated with increased germline mutations and epigenetic alterations that may influence offspring growth, cognition, and health (D'Onofrio et al., 2014; Jenkins et al., 2014; Johnson et al., 2015; Kong et al., 2012). Maternal age is linked to declining oocyte quality, altered placental function, and an increased risk of obstetric complications, all of which may constrain fetal growth and affect long-term health (Jolly et al., 2000; Lean et al., 2017; Pinheiro et al., 2019; Tarín et al., 1998). In addition, social factors including age-assortative mating, a common human pattern shaped by socioeconomic and marital norms (Epstein & Guttman, 1984; Luo, 2017; Spuhler, 1968), may affect family resources and early-life environments, thereby indirectly influencing offspring growth and development. Together, these biological and social processes suggest that parental age and reproductive timing may contribute to variation in offspring phenotype. Although parental-age effects have been widely documented in epidemiological and biomedical research, their contribution to normal-range human morphological variation remains poorly understood.

Within biological anthropology, variation in body size and craniofacial morphology has been studied primarily in relation to nutrition, developmental stress, health, and socioeconomic conditions (e.g., Bogin, 2021; Hallgrímsson et al., 2007; Martínez-Abadías et al., 2012). Research on somatic growth has focused largely on outcomes such as birth weight, growth trajectories, and adult stature, with paren-

tal influences generally found to be small, context-dependent, and strongly mediated by environmental conditions (Bogin, 2021; Eveleth & Tanner, 1990; Ulijaszek et al., 1998). Similarly, studies of craniofacial morphology have emphasized environmental and developmental influences, while parental age has rarely been examined as a potential determinant of craniofacial variation (Hallgrímsson et al., 2007; Martínez-Abadías et al., 2012). Consequently, despite extensive evidence that craniofacial traits are sensitive to developmental and environmental conditions, the contribution of parental age to craniofacial variation remains largely unexplored.

Using anthropometric data collected from military cadets in pre-World War II Lviv, this study investigates how parental age relates to variation in offspring body size and craniofacial morphology. Craniofacial traits may be particularly informative for detecting subtle developmental influences because they reflect both genetic inheritance and sensitivity to environmental conditions during growth (Hallgrímsson et al., 2007; Martínez-Abadías et al., 2012). Moreover, the historical context, characterized by high-fertility, socioeconomic instability, and major disruptions such as war and pandemic, provides a unique opportunity to examine parental-age effects in a population exposed to substantial environmental stress. By integrating parental, familial, and historical factors, this study contributes to a broader anthropological understanding of how reproductive timing may shape human morphological variation.

Main Aims

First, to examine associations between parental age and the anthropometric traits of their sons in a sample of pre-World

War II cadets from Lviv. Second, to assess additional sources of variation influencing these traits, including socioeconomic status (parental occupation, family size), environmental exposures (place of origin, temporal trends related to World War I (WWI) and the Spanish flu), and family mortality (including parental and sibling deaths). While the study considers multiple sources of variation, its primary focus was on the relationship between parental age and offspring morphology.

Hypothesis

Parental age differences may influence body and craniofacial dimensions through three mechanisms: (1) paternal age effects, such as mutation accumulation and epigenetic changes; (2) maternal age effects, including reduced oocyte quality and increased obstetric complications; and (3) social mechanisms reflected in age-assortative mating. These mechanisms may operate independently or interactively, and their influence may be pronounced under historical conditions of war, disease, and socioeconomic instability.

Material and Methods

The present study is based on archival anthropometric records collected between 1933 and 1938 as part of routine medical examinations conducted at Cadet Corps No. 1 in Lviv. Measurements were obtained by Franciszek Wokroj at the Department of Anthropology of the Jan Kazimierz University in Lviv and included cadets from all companies of the corps (Wokroj, 1949). The dataset is entirely archival and has been preserved in university collections.

Cadet Corps No. 1 in Lviv was an inter-war Polish military-educational institution

within a broader system of pre-military training designed to prepare adolescents for military service. Considered one of the leading military schools of the Second Polish Republic, it primarily attracted sons of military officers and members of the intelligentsia. Following major expansion and modernization during the 1920s, the corps became a model institution frequently visited by Polish and foreign military representatives. Admission typically occurred after completion of primary education at approximately 12–14 years of age. The school operated as a boarding institution under the Ministry of Military Affairs and was characterized by a highly structured daily routine and strict discipline (Wyszczelski & Niewęłowska, 2016).

The sample comprised 365 males and represents a mixed cross-sectional cohort including both active cadets and former students. Participants were born between 1893 and 1920 (mean birth year = 1916.2 ± 3.2) and ranged in age from 18 to 45 years at the time of examination (mean age = 21.8 ± 3.2 years). The relatively broad age range reflects the inclusion of graduates who remained under institutional medical supervision or participated in follow-up examinations.

Anthropometric measurements were collected during routine medical examinations performed by the cadet health service and followed the standardized protocols of the Lviv anthropological school described by Wokroj (1949). All measurements were obtained from living individuals and therefore represent soft-tissue anthropometry. Each record contained demographic and social information, including place and date of birth, parental occupation, and educational affiliation. Anthropometric data included five body measurements and ten craniofacial measurements (Table 1).

Table 1. Summary of anthropometric measurements with landmark definitions, mean values, standard deviations (SD), and measurement units for all traits available in the dataset (n = 365 men)

Measurement	Landmark/Definition	Mean	SD	Unit
Body weight		64.2	7.0	kg
Body height		171.5	6.3	cm
Body mass index	weight / (height ^ 2)	21.8	2.1	kg/m ²
Chest circumference	during inhalation	90.3	4.5	cm
Chest circumference	during exhalation	79.8	4.2	cm
Head length	glabella-opisthocranion	188.3	6.4	mm
Head width	euryon-euryon	157.2	5.6	mm
Mastoid width	mastoid-mastoid	131.9	6.3	mm
Forehead width	frontotemporale-frontotemporale	108.0	4.2	mm
Face width	bizygomatic width	139.5	5.6	mm
Jaw width	bigonial width	107.1	5.6	mm
Face height	nasion-gnathion	119.9	7.2	mm
Upper face height	nasion-prosthion	69.0	4.4	mm
Nasal height	nasion-subnasale	50.3	3.8	mm
Nasal width	alare-alare	34.0	2.4	mm

Paternal age at birth was available for 250 boys (68.5%), ranging from 18 to 54 years (mean = 33.1 ± 6.5 years). Maternal age at birth was available for 286 boys (78.4%), ranging from 13 to 50 years (mean = 26.3 ± 6.3 years). Parental age difference (paternal age minus maternal age) was available for 228 boys (62.5%), ranging from -2 to 27 years (mean = 7.2 ± 5.2 years), indicating fathers were generally older than mothers.

To reduce dimensionality and summarize correlated craniofacial measurements, Principal Component Analysis (PCA) was performed on standardized craniofacial variables. Components with eigenvalues greater than 1 (Kaiser criterion) were retained for further analyses.

Two components met this criterion. PC1 explained 36.8% of the variance and reflected overall craniofacial size, with strong loadings from cranial and facial length, width, and height measures. PC2 explained 20.9% of the variance and represented craniofacial shape, being primarily influenced by facial and nasal height dimensions.

Statistical analyses included Spearman's rank correlations (ρ) to assess associations among parental-age variables, family characteristics, and the anthropometric traits of their sons. Subsamples were compared using Mann-Whitney U tests. Non-parametric methods were used because several variables deviated from normality.

Generalized Additive Models (GAMs) were fitted for each anthropometric trait to evaluate associations with parental-age variables while adjusting for potential confounders. GAMs were chosen because parental-age effects may not be strictly linear, and these models allow flexible estimation of non-linear relationships using smooth functions while retaining the interpretability of regression models. The models included paternal age, maternal age, and parental age difference as predictors, together with individual age at measurement, birth year, place of origin (town = 35.0%, city = 65.0%; after Scheinkönig & Kowalczewski, 1934), parental occupation (worker/peasant = 25.1%, craftsman = 4.1%, white-collar worker = 50.9%, trader = 9.7%, other = 10.1%; after Szturm de Sztrem, 1931), number of children in family (mean = 3.8, range = 1–13), and number of deceased siblings (none = 78.1%, one sibling = 13.4%, two or more siblings = 8.5%, range = 0–8). The significance of both smooth and parametric terms was assessed using the test statistics and associated p-values reported by the GAM. Significant terms indicated that a predictor explained variation in the anthropometric trait after adjustment for the other variables included in the model.

Results

Family correlations

Maternal and paternal ages were strongly correlated ($\rho = 0.646$, $p < 0.001$), consistent with age-assortative mating. Parental age differences correlated negatively with maternal age ($\rho = -0.269$, $p < 0.001$) and positively with paternal age ($\rho = 0.503$, $p < 0.001$), suggesting that younger women often married older men.

Family size was moderately positively correlated with sibling mortality ($\rho = 0.310$, $p < 0.001$), indicating higher child loss in larger families.

Associations between parental ages and anthropometry

Spearman correlations (Table 2) indicated generally weak associations between parental-age variables and anthropometric traits of their sons, with correlation coefficients not exceeding $|\rho| = 0.16$. Jaw width was the only trait significantly associated with parental age, showing weak negative correlations with parental age difference ($\rho = -0.14$, $p = 0.04$) and paternal age ($\rho = -0.16$, $p = 0.02$), indicating slightly smaller jaw width among sons of older fathers and parents with larger age differences. Additional weak negative trends were observed between maternal age and body height ($\rho = -0.12$) and nasal height ($\rho = -0.12$), as well as between paternal age and overall craniofacial size (PC1; $\rho = -0.13$). However, these relationships did not reach statistical significance ($0.05 \leq p < 0.10$).

GAMs (Table S1) identified relatively few significant associations, broadly consistent with the weak correlations observed. Head length decreased significantly with parental age difference ($F = 6.04$, $p = 0.04$), with a weaker contribution from maternal age ($F = 4.77$, $p = 0.08$). Craniofacial size (PC1) was significantly associated with paternal age ($F = 2.16$, $p = 0.05$), whereas craniofacial shape (PC2) varied with parental age difference ($F = 3.15$, $p = 0.02$). Additional weak patterns were observed between paternal age and jaw width ($F = 5.79$, $p = 0.07$) and nasal height ($F = 2.23$, $p = 0.06$), although these associations were not statistically significant.

Table 2. Spearman's rank correlations (ρ) and corresponding p-values between parental age variables (paternal age, maternal age, and parental age difference) and the anthropometric traits of their sons

	Paternal age		Maternal age		Parental age difference	
	ρ	p-value	ρ	p-value	ρ	p-value
Body weight	0.055	0.417	0.077	0.257	0.005	0.946
Body height	-0.004	0.953	0.122	0.071*	-0.113	0.094*
Body mass index	0.059	0.381	-0.002	0.982	0.071	0.296
Chest circumference (inhale)	0.097	0.153	0.102	0.133	0.036	0.600
Chest circumference (exhale)	0.091	0.180	0.059	0.387	0.066	0.333
Head length	-0.047	0.491	0.073	0.280	-0.105	0.119
Head width	-0.082	0.227	-0.022	0.742	-0.029	0.664
Mastoid width	-0.057	0.401	0.034	0.615	-0.054	0.427
Forehead width	-0.078	0.251	-0.060	0.376	0.013	0.846
Face width	-0.096	0.156	-0.023	0.739	-0.069	0.311
Jaw width	-0.159	0.018**	-0.019	0.778	-0.140	0.038**
Face height	-0.060	0.376	0.010	0.883	-0.080	0.236
Upper face height	-0.015	0.826	0.068	0.312	-0.089	0.190
Nasal height	-0.014	0.839	0.122	0.072*	-0.119	0.078*
Nasal width	0.004	0.949	0.007	0.917	-0.026	0.699
PC1 (craniofacial size)	-0.130	0.054*	0.006	0.930	-0.122	0.071*
PC2 (craniofacial shape)	0.076	0.260	0.074	0.273	-0.008	0.908

Note: ρ = Spearman's rank correlation coefficient. Significance codes: ** $p < 0.05$, * $p < 0.1$.

Other sources of variation

Body height was higher in sons of white-collar workers ($\beta = 2.58$, $p = 0.02$), while body weight was higher in sons of traders/good owners ($\beta = 3.83$, $p = 0.03$), compared to sons of workers/peasants. A weak association was observed between craniofacial shape (PC2) and urban versus rural origin ($\beta = 0.40$, $p = 0.06$), although this relationship did not reach statistical significance.

Sibling mortality also influenced several traits including body height ($\beta = -2.72$, $p = 0.05$), nasal height ($\beta = 2.11$, $p = 0.02$), and craniofacial size (PC1; $\beta = 1.09$, $p = 0.02$). All GAM results are presented in Table S1.

Family size and birth-year effects were not significant in GAMs, and comparisons between small (1–2 siblings, $n = 196$) and large families (3 and more siblings, $n = 169$) revealed no significant differences in any anthropometric trait (all $p > 0.05$). In contrast, comparisons between birth cohorts corresponding to major historical events revealed several differences. Individuals born in 1914 or later ($n = 315$) exhibited smaller jaw width than those born before 1914 ($n = 50$; $W = 6247$, $p = 0.02$). Similarly, individuals born in 1918 or later ($n = 154$) had smaller jaw width ($W = 13676$, $p = 0.01$), lower body weight ($W = 13180$, $p = 0.01$), and lower

BMI ($W = 11590$, $p < 0.001$) than those born before 1918 ($n = 211$).

Comparisons of subsamples with missing data

Parental mortality was relatively common in the sample: 26.6% of boys had lost at least one parent by the time of measurement (20.0% paternal mortality and 11.2% maternal mortality), reflecting the impacts of WWI (particularly the nearly twofold higher mortality of fathers) and the Spanish flu pandemic of 1918–1920. Consequently, parental-age data were unavailable for 37.5% of the sample (137 of 365 boys), reducing the effective sample size and potentially introducing bias.

To evaluate possible selective missingness, individuals with known and unknown parental ages (when at least one parent died) were compared for all anthropometric traits that showed significant associations or weak patterns. No significant differences were found for body height ($W = 15243$, $p = 0.86$), weight ($W = 15019$, $p = 0.84$), jaw width ($W = 13628$, $p = 0.06$), head length ($W = 15114$, $p = 0.69$), nasal height ($W = 16871$, $p = 0.17$), PC1 ($W = 15608$, $p = 0.99$), or PC2 ($W = 16828$, $p = 0.22$). These comparisons provide no evidence that missing parental-age data were associated with the anthropometric traits examined, although the possibility of non-random missingness cannot be excluded.

Discussion

The strong positive correlation between maternal and paternal ages reflects pronounced age-assortative mating, a pattern well documented in historical and contemporary societies (Epstein & Gutt-

man, 1984; Luo, 2017; Spuhler, 1968). The observed age-gap asymmetry (older fathers and younger mothers) aligns with demographic and evolutionary expectations (Buss, 1989; Geary et al., 2004): men often delayed marriage until achieving economic stability, whereas women married earlier due to reproductive constraints and prevailing marital norms.

The positive association between larger family and sibling mortality is consistent with established mechanisms. Resource dilution reduces per-child parental investment as family size increases (Blake, 1981). Larger households also facilitate transmission of infectious diseases, historically a major cause of early-life mortality (Preston & Haines, 1991). High-fertility families were additionally more likely to experience crowding or poor sanitary conditions, compounding environmental risks.

Associations between parental age and offspring anthropometric traits were generally weak. Most relationships were small in magnitude and statistically non-significant, with only a limited number of craniofacial traits showing significant associations.

Advancing paternal age was associated with smaller jaw width and variation in overall craniofacial size (PC1), whereas maternal age exhibited only weak, non-significant trends. Although the observed effects were modest, previous research has proposed that advancing parental age may influence offspring development through mechanisms such as germline mutation accumulation and age-related reproductive constraints (Liu et al., 2011; Tarín et al., 1998; Zhang et al., 2022). However, the present findings provide only limited support for individual parental-age effects on anthropometric variation.

Parental age difference was associated with smaller jaw width, shorter head length, and variation in craniofacial shape (PC2). Larger age differences between parents may reflect broader life-history variation, including differences in health, socioeconomic background, reproductive timing, or investment capacity, all of which may influence developmental conditions during early life (Hill & Kaplan, 1999; Myrskylä & Fenelon, 2012). Nevertheless, the observed associations were weak, suggesting that parental age difference contributed only modestly to variation in the anthropometric traits examined.

A plausible explanation for the weak parental-age effects is early-life selection. With nearly one-quarter of families experiencing sibling deaths, high infant and child mortality likely removed the most vulnerable individuals. Consequently, surviving children represent a genetically and physiologically hardier subset, reducing variation in observed traits and masking stronger underlying associations between parental characteristics and anthropometry.

Sample homogeneity likely further constrained detectable variation. Military cadets represented a selective group due to competitive admission procedures and health requirements, which may have reduced variation in physical and developmental characteristics, including body size. In contrast, specific craniofacial traits, including jaw width, head length, and overall craniofacial size and shape, being less directly influenced by general growth and nutrition, showed relatively greater sensitivity to subtle parental-age, family-structure, and environmental effects.

Socioeconomic differences were also associated with anthropometric varia-

tion. Sons of higher-status parents exhibited greater height and weight, consistent with better access to nutrition, household stability, and caregiving quality (Bradley & Corwyn, 2002). Occupation, however, captures only part of socioeconomic variation; correlated factors such as parental education, parenting practices, and social capital may further contribute to offspring outcomes.

Sibling mortality was associated with body height, nasal height, and overall craniofacial size among surviving offspring, potentially reflecting two complementary mechanisms. First, surviving children may represent genetically hardier individuals with better immune function and growth potential (selection effect). Second, the loss of siblings may concentrate household resources (food, parental attention, financial investment) on survivors, enhancing growth through reduced competition (resource reallocation effect).

Finally, birth cohorts corresponding to the periods of WWI and the Spanish flu exhibited smaller jaw width, while individuals born during or after the Spanish flu period also showed lower body weight and BMI. These patterns are consistent with studies demonstrating long-term growth deficits following wartime stress and early nutritional deprivation (Mazumder et al., 2010; Palloni et al., 2020).

Research Limitations

Several limitations should be considered when interpreting the findings. First, the dataset comprises a relatively homogeneous cohort of male military cadets, with 94.8% born in the 1910s, introducing potential selection bias. The sample was socially and educationally selective, reflecting competitive selection process

and general health requirements. Consequently, the findings may not be representative of the broader population, and associations with parental age or socioeconomic factors may differ in more diverse populations or among females. At the same time, this homogeneity may have reduced confounding from broader social and historical influences, thereby increasing internal consistency. Nevertheless, the findings should be generalized with caution.

A second limitation concerns missing parental-age data, which were unavailable for 37.5% of the sample, partly due to parental mortality associated with WWI and the Spanish flu pandemic. Comparisons between individuals with known and unknown parental ages revealed no significant differences in the anthropometric traits examined, suggesting no obvious pattern of selective missingness in the measured outcomes. However, the missingness was unlikely to be completely random, as parental mortality may have been associated with unmeasured factors such as socioeconomic conditions, parental health, or wartime experiences. Therefore, the possibility of residual bias cannot be excluded.

An additional limitation is the lack of information on intra- and inter-observer measurement error. Because the study relies on archival records collected in the 1930s, measurement reliability cannot be assessed retrospectively. Although measurements were obtained according to the standardized protocols of the Lviv anthropological school (Wokroj, 1949), it remains possible that measurement error influenced the observed associations.

Finally, given the number of statistical tests performed, some significant findings may reflect Type I error. The results should therefore be interpreted

cautiously and regarded as exploratory until replicated in independent datasets. Future studies based on larger, more diverse, or longitudinal samples are needed to determine whether the weak associations observed here reflect broader biological processes or are specific to this historical cohort.

Additional information

Supplementary materials [online version].

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Author contributions

LK: Formal analysis; methodology; writing – original draft preparation; writing – review & editing (lead). GL: Conceptualization; data curation; supervision; writing – review & editing (supporting).

Ethics statement

The data were obtained from the archives of the Institute of Human Biology and Evolution at Adam Mickiewicz University, Poznań. The 1938 study of cadets from Corps No. 1 in Lviv was conducted by Professor Franciszek Wokroj (1949) under the ethical and professional norms of his time. Formal bioethics review did not exist in Poland until the 1990s. Nevertheless, all procedures followed institutional and national ethical and methodological standards. Personal data in this study were processed in accordance with Recitals 27, 158, and 150 and Article 89

of Regulation 2016/679 (GDPR), with appropriate measures taken to respect the rights of the participants.

Data availability statement

The data that support the findings of this study are available from the authors upon reasonable request.

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Conflict of interest

The authors declare that there are no conflicts of interest related to this manuscript.

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SUPPLEMENTARY MATERIALS

The role of parental age, family dynamics, and historical adversity in craniofacial variation of pre-World War II cadets

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Table S1. Generalized Additive Model (GAM) results for associations between parental age variables (paternal age, maternal age, and parental age difference) and anthropometric traits of sons. Models include smooth terms for individual age at measurement, birth year, and number of children in the family, and parametric coefficients for place of origin, parental occupation, and number of deceased siblings

	Body height				Body weight			
Smooth terms:	Edf	Ref.df	F-value	p-value	Edf	Ref.df	F-value	p-value
Paternal age	2.104	2.638	1.977	0.184	0.590	0.590	1.699	0.318
Maternal age	1.298	1.689	0.994	0.238	0.676	0.676	0.914	0.433
Parental age difference	0.735	0.735	0.599	0.508	0.735	0.735	0.058	0.836
Age of individual	0.772	0.944	0.853	0.371	1.411	1.649	0.200	0.830
Birth year	0.772	0.944	0.853	0.371	1.411	1.649	0.200	0.830
Number of children	1.000	1.000	0.003	0.959	1.000	1.000	0.814	0.368
Parametric coefficients:	Estimate	SE	t-value	p-value	Estimate	SE	t-value	p-value
One deceased sibling	-2.724	1.371	-1.987	0.048**	-0.320	1.553	-0.206	0.837
Two or more deceased siblings	-1.700	1.613	-1.054	0.293	2.125	1.840	1.155	0.250
Place of origin (city)	-1.226	0.937	-1.308	0.192	-0.828	1.073	-0.771	0.441
Occupation (craftsman)	3.164	2.246	1.409	0.161	1.967	2.543	0.774	0.440
Occupation (white-collar)	2.581	1.118	2.309	0.022**	2.059	1.276	1.614	0.108
Occupation (trader)	2.576	1.583	1.628	0.105	3.832	1.785	2.146	0.033**
Occupation (other)	0.474	1.597	0.297	0.767	1.685	1.826	0.922	0.358
	Head length				Jaw width			
Smooth terms:	Edf	Ref.df	F-value	p-value	Edf	Ref.df	F-value	p-value
Paternal age	0.589	0.589	0.126	0.785	0.589	0.589	5.786	0.066*
Maternal age	0.675	0.675	4.765	0.075*	0.675	0.675	0.088	0.807
Parental age difference	0.736	0.736	6.038	0.036**	1.267	1.629	1.963	0.274
Age of individual	0.500	0.500	0.158	0.779	0.500	0.500	0.185	0.761
Birth year	0.500	0.500	0.158	0.779	0.500	0.500	0.185	0.761
Number of children	1.000	1.000	1.162	0.282	1.000	1.000	0.232	0.631
Parametric coefficients:	Estimate	SE	t-value	p-value	Estimate	SE	t-value	p-value
One deceased sibling	1.382	1.561	0.885	0.377	-0.268	1.191	-0.225	0.822
Two or more deceased siblings	2.543	1.848	1.376	0.170	2.397	1.409	1.701	0.091*
Place of origin (city)	1.305	1.058	1.233	0.219	-0.896	0.807	-1.110	0.268
Occupation (craftsman)	-0.122	2.572	-0.048	0.962	-1.339	1.967	-0.681	0.497
Occupation (white-collar)	0.354	1.270	0.279	0.781	-1.175	0.969	-1.213	0.227
Occupation (trader)	1.626	1.798	0.904	0.367	-2.292	1.371	-1.672	0.096*
Occupation (other)	3.001	1.767	1.699	0.091*	-0.500	1.351	-0.370	0.712

Note: Edf = effective degrees of freedom; Ref.df = reference degrees of freedom; SE = standard error. Significance codes: **p<0.05, *p<0.1.

Table S1 (continued)

	PC1 (craniofacial size)				PC2 (craniofacial shape)			
Smooth terms:	Edf	Ref.df	F-value	p-value	Edf	Ref.df	F-value	p-value
Paternal age	3.305	3.541	2.159	0.048**	0.589	0.589	3.239	0.169
Maternal age	0.675	0.675	0.239	0.688	0.675	0.675	0.007	0.944
Parental age difference	2.347	2.887	2.515	0.115	3.408	3.669	3.146	0.021**
Age of individual	1.085	1.312	0.163	0.816	0.500	0.500	2.064	0.311
Birth year	1.085	1.312	0.163	0.816	0.500	0.500	2.064	0.311
Number of children	1.000	1.000	0.327	0.568	1.000	1.000	0.061	0.805
Parametric coefficients:	Estimate	SE	t-value	p-value	Estimate	SE	t-value	p-value
One deceased sibling	-0.405	0.388	-1.044	0.298	0.146	0.310	0.471	0.638
Two or more deceased siblings	1.091	0.454	2.404	0.017**	0.314	0.366	0.859	0.391
Place of origin (city)	-0.221	0.262	-0.842	0.401	0.395	0.209	1.888	0.061*
Occupation (craftsman)	-0.265	0.634	-0.418	0.676	-0.387	0.513	-0.755	0.451
Occupation (white-collar)	-0.240	0.311	-0.771	0.442	0.234	0.251	0.933	0.352
Occupation (trader)	-0.207	0.445	-0.466	0.642	-0.006	0.355	-0.018	0.986
Occupation (other)	-0.123	0.452	-0.273	0.785	0.211	0.352	0.599	0.550
Nasal height								
Smooth terms:	Edf	Ref.df	F-value	p-value				
Paternal age	3.197	3.501	2.230	0.064*				
Maternal age	0.675	0.675	0.257	0.677				
Parental age difference	1.007	1.230	0.898	0.460				
Age of individual	0.500	0.500	0.378	0.664				
Birth year	0.500	0.500	0.378	0.664				
Number of children	1.000	1.000	0.429	0.513				
Parametric coefficients:	Estimate	SE	t-value	p-value				
One deceased sibling	-0.331	0.785	-0.422	0.674				
Two or more deceased siblings	2.114	0.919	2.299	0.023**				
Place of origin (city)	0.750	0.530	1.416	0.158				
Occupation (craftsman)	-1.065	1.282	-0.831	0.407				
Occupation (white-collar)	0.450	0.631	0.714	0.476				
Occupation (trader)	0.197	0.905	0.217	0.828				
Occupation (other)	-0.200	0.889	-0.224	0.823				

Note: Edf = effective degrees of freedom; Ref.df = reference degrees of freedom; SE = standard error. Significance codes: **p<0.05, *p<0.1.

Research dynamics in the applicability of radiological mandibular parameters for forensic sex and age estimation: A systematic review

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Abstract

INTRODUCTION

The mandible is the largest and strongest bone of the human facial skeleton. The absence of any overlying bony structure makes it suitable for radiological imaging in both living as well as deceased or skeletonized individuals. In this systematic review we aim to aid forensic practitioners in making informed decisions about the techniques and parameters involving the human mandible to ensure high quality and credibility of forensic analyses needed for medico-legal as well as humanitarian purposes.

AIM

Our review investigates the research dynamics and utility of radiological mandibular dimensions for forensic sex and age estimation.

METHODOLOGY

Out of 175 articles obtained from scientific databases including PubMed, Google Scholar, Web of Science and Scopus, 55 full-text articles were found eligible for this systematic review. The articles were extracted systematically considering the authorship, year of publication, country, population studied, the mandibular parameters and radiological modality used, sample size, and age thresholds of the subjects.

RESULTS AND DISCUSSION

The maximum number of studies (60%) used radiological mandibular dimensions for sex estimation and 38% researchers estimated both sex and age from these parameters. 69.1% (n=38) articles used panoramic radiographs, 21.8% (n=12) articles utilized cone beam computed tomography/computed tomography scans and only four articles used cephalometric scans for sex and/or age estimations. Orthopantomograms (OPGs) were found to be the more commonly used imaging modality in clinical practice. The majority of studies reported mandibular ramus height as the most reliable parameter for sex and age estimation. Fewer than



Original article

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half of the studies reported accuracy percentages of their estimations; around 70% of them reported accuracies below the acceptable forensic thresholds, thus clearly indicating that sex and age estimation should not be performed based on mandibular measurements only.

CONCLUSION

This systematic review is expected to inform future forensic anthropologists that only mandibular morphometry should not be attempted for human identification in medico-legal contexts.

KEYWORDS: Forensic anthropology, identification, mandibular radiological parameters, mandible morphometry

Introduction

Estimating sex and age-at-death, reconstructing stature and deciphering population affinity are the important components of biological profile of an individual's identity in forensic anthropology (Bhatnagar & Pokhrel, 2013). Forensic anthropological analyses provide crucial details about the identity credential of unknown human skeletal remains retrieved from different contexts (Arthanari et al., 2022), and such analyses may help medico-legal experts in their investigations and bringing closure comfort to the families of the deceased. Human remains need to be accurately identified and linked to the missing persons or the victims of crimes or disasters (Huomonen et al., 2010). In different instances of mass disasters, the human bodies or remains are often found unrecognizable, heavily damaged, commingled and fragmented, thus establishing identity of such remains become challenging for the experts (Jambunath et al., 2016).

The mandible is the largest and the most robust bone of the human facial skeleton (Breeland et al., 2025) and is considered as one of the most sexually dimorphic element of the craniofacial skeleton. It is the exploitable shape and size, patterned growth indicators, dense and compact nature of mandible which render it as the commonly preserved and most studied part of human skull for forensic anthropological purposes (Kumar et al., 2016; More et al., 2017). Owing

to the basic structural characteristics associated with mandibles such as dense cortical structure and resistance to post-mortem damage, this facial bone is frequently recovered intact in different situations involving fragmentation, burning, or damage/fracture; mostly encountered in mass disaster incidents. Considering its durable morphology and conveniently measurable morphometry, it qualifies as a valuable skeletal element for forensic identifications, particularly in sex estimation (Abu-Taleb & El Beshlawy, 2015; Behl et al., 2020; Kumar et al., 2016).

Sexual dimorphism of the mandible is reflected in its shape and size with male bones generally being bigger and more robust than the female bones (Raj & Ramesh, 2013); its patterned growth indicators may also provide some valuable clues about age of an individual. Its morphological features may contribute to discern the age, sex and population affinity and, thus identity of an individual, though it may be influenced by the dietary habits and age-group of the individual (Al-Shamout et al., 2012). Forensic anthropologists analyze the well-marked mandibular features such as chin profile, ascending ramus pinching, mental foramen, mandibular torus, gonial eversion, dental structures and pathology, and some other morphological and metrical features. Different mandibular measurements (measured on the bone or its radiological images) have been used for identifying the living as well as the skeletonized individuals. The ease of taking radiographs of mandible is a key

factor for choosing it for radiological examinations in forensic scenarios (Kumar et al., 2016; Shamim et al., 2006), though the shadow from some overlying structures (like zygomatic bone and vertebral bodies) may disrupt correct imaging or its analyses. Various panoramic mandibular parameters have offered multifaceted deep insights into age and sex estimations and the assessment of population affinities (Zangouei-Booshehri et al., 2012), particularly in cases of mass disasters, exhumed remains, mutilations, and missing person scenarios where severely damaged, burnt and fragmented human remains are available for biological profiling purposes.

Different linear and angular parameters/dimensions of the mandible have been recorded by various researchers using different radiological techniques like panoramic radiographs (OPGs), cone beam computed tomographs (CBCT), cephalograms and others. Among these parameters, the mandibular length, ramus height, ramus width, mandibular angle, mental index, coronoid height, mental eminence and symphysis width stand out for its diagnostic potential for different forensic purposes (e.g., Abu-Taleb & El Beshlawy, 2015; Ingaleshwar et al., 2022; Kanya et al., 2017; Karmarkar et al., 2023; Meleveetil et al., 2020). The two-dimensional (2D) modalities like OPGs have been found easy to use, cost effective and more informative to analyze mandibular skeletal features. Also, oral OPGs have been reported as one of the most common imaging methods for routine examination in clinical practice (More et al., 2017). One study reported that orthopantomograms (OPGs) are a useful tool for the measurement of mandible, though there are some magnification and distortion issues with the use of OPGs for forensic purposes (Indira et al., 2012; Kumar et al., 2016; Sambhana et al.,

2016). On the other hand, three-dimensional (3D) modalities such as cone beam computed tomography (CBCT), have been widely used for procedures such as dental implants and orthodontic treatment. Cone beam computed tomography can be considered advantageous due to its high spatial resolution, short scan time and rapid image acquisition. Cone beam computed tomography also provides accurate and reliable linear measurements, making it especially valuable for the evaluation and reconstruction of dental and maxillofacial structures. Furthermore, it enables three-dimensional reconstruction of mandibular features with minimal distortion and negligible magnification, thereby allowing precise and dependable assessment for age and sex estimation (Abd Elsalam et al., 2019; İlgüy et al., 2014). Digital orthopantomograms (OPGs), on the other hand, have been widely utilized in forensic investigations due to their accessibility and routine use in dental practice. Their applicability is attributed to their ability to capture broad maxillofacial structures with relatively low radiation exposure. Several studies have reported that OPGs provide reliable and reasonably accurate linear and angular measurements for mandibular morphometric assessment, owing to their relatively uniform magnification and minimal distortion (Ayesha et al., 2022; Sambhana et al., 2016). The conventional 2D or 3D CT is a valuable imaging technique used for forensic identifications, offering numerous advantages over the traditional radiological projections. These advantages may range from eliminating structural superimposition to visualising subtle density differences, with a strong capacity to generate accurate 3D reconstructions that have the ability to enhance forensic anthropometric measurements and individual identification (Kallalli et al., 2016).

In this study we conduct a systematic literature review to identify the most accurate and reliable mandibular parameters for age and sex estimation, to report the imaging techniques that provide the highest accuracy, and to evaluate and quantify the associated geographic variations in different mandibular parameters. The main aim is to highlight the current research dynamics in the application of mandibular radiological dimensions for forensic anthropological sex and age estimations using different radiological modalities and, to identify any consistent patterns, discrepancies, under-researched areas, prospects and directions in the field.

Material and Methods

Search strategy

A comprehensive search of scientific literature, published from 2010 to 2024, was carried out from databases of scientific search engines of PubMed, Google Scholar, Web of Science and Scopus. A time-frame of 15 years was selected to study methodological consistency and research trends in a specific time duration. As the application of radiological imaging modalities in forensic anthropology increased with the advent of CT and CBCT imaging, as well as with the improvements in voxel resolution and radiological measurement techniques, focus was on radiological mandibular parameters (McCollough & Rajiah, 2023; Patyal & Pandey, 2023; Sehrawat & Ahlawat, 2023). The search strategy included a combination of keywords and Boolean operators like “mandibular parameters”, “sex estimation”, “age estimation”, “radiological method”, “panoramic radiographs (OPGs)” and “cone beam computed tomographs (CBCT)”. The search strings used were “sex” and “age”, and “estimation” and “from” and “mandibular” and “param-

eters” and “using radiological” and “techniques”. To enhance the search strategy, the above said keywords focusing on the anatomical mandibular aspects, forensic purposes, imaging modalities, and variations in radiological methodologies etc., were employed. Furthermore, Boolean operators (such as AND, OR) were applied in combination with the search terms to maximize the sensitivity and specificity of the search; the non-Boolean linking words (such as prepositions) were not treated as part of the Boolean operators, though they might have been included as part of the titles or abstracts of the indexed articles. The extracted references obtained from the literature search were imported into Mendeley Reference Manager v2.115.0 desktop application and any duplicates were removed using the ‘merge’ option under the ‘duplicate items’ section.

Inclusion criteria

Original research articles that used mandibular parameters for sex and/or age estimation based on radiological methods like OPGs, CBCT scans or panoramic radiographs were included in the study. Studies providing detailed methodological descriptions and statistical analyses, conducted with individuals from diverse geographical regions, using varied research designs and published in forensic journals during the considered timeframe (2010–2024) were considered.

Exclusion criteria

Articles describing case reports, reviews, editorials or conference abstracts/proceedings, and pre-prints were excluded from consideration in the present study. Articles not available in full-text, written in language other than English, having insufficient methodological details and reporting high error rates/bias were ignored

for inclusion in this systematic review. Finally, full-text articles/studies not mentioning the sample size and those presenting incomplete data were also excluded.

Study selection and data extraction

Data were collected in three different stages. Firstly, studies were identified from the scientific databases using keywords as outlined above. Studies mentioning mandibular measurements like gonial angle, ramus height, coronoid height, and condylar height in analysis were considered

for further evaluation as these parameters had reported consistent and statistically significant sexual dimorphism in mandible (Abd Elsalam et al., 2019; Esfehiani et al., 2023; Kallalli et al., 2016; Sambhana et al., 2016). Data from the selected articles were extracted in a systematic manner which included: authorship, year of publication, country/geographic region, population studied, mandibular parameters/measurements used, radiological modality utilized, sample size and age ranges of the study subjects (Table S1, Figure 1).

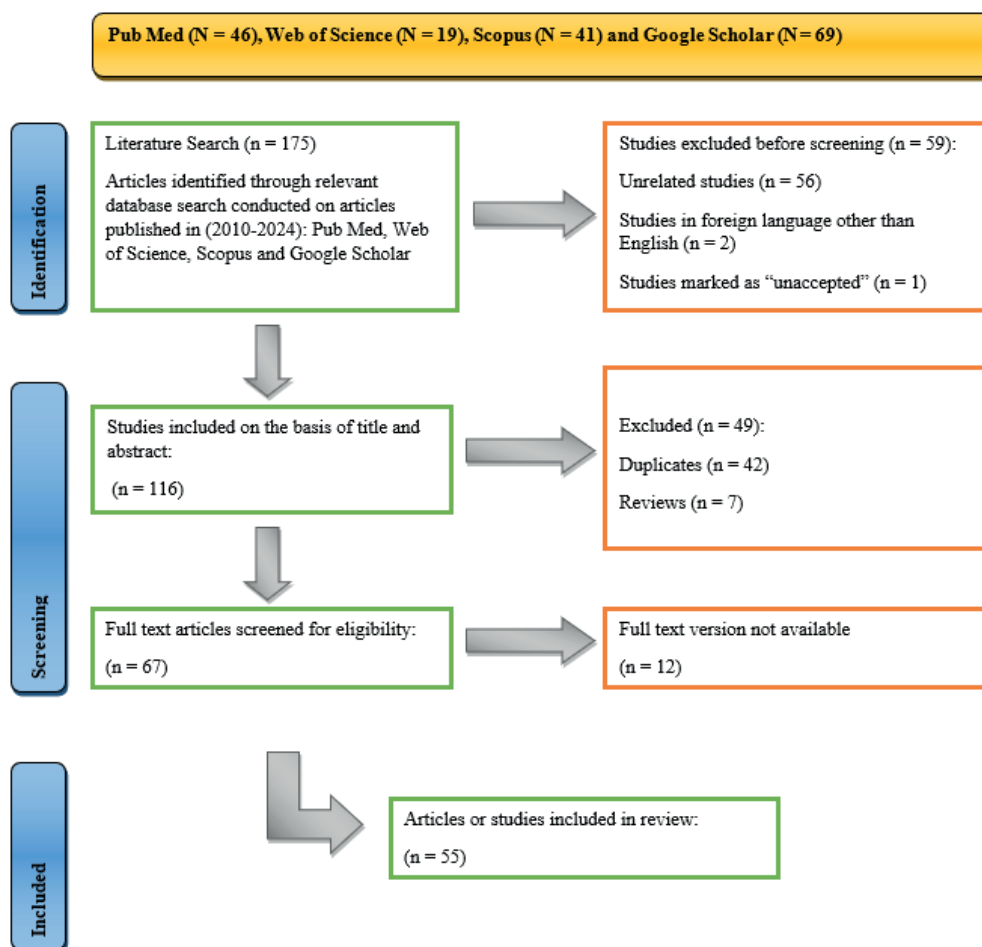


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA flowchart showing exclusion and inclusion criteria of studies in the present systematic review.

Quality assessment/ Risk of Bias (ROB) Assessment

The methodological rigor of the included studies was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklists, as they are an internationally recognized tool for assessing the methodological quality of systematic reviews (Moola et al., 2020). This tool is structured in such a manner that specific criteria are enhanced through its design which increases transparency, reproducibility, and comparability across studies. Furthermore, this tool evaluates eight domains including clarity of inclusion criteria, description of study setting, validity and reliability of exposure measurements, identification and management of confounding factors, outcome assessment, and appropriateness of the statistical analyses used (Moola et al., 2020). Each study was independently evaluated by two reviewers (JS and ST) and categorized as having low, moderate, or high risk of bias, based on the number of criteria fulfilled. Each item was scored as "Yes" (1), "No" (0), or "Unclear" (0). The study quality assessment level was calculated as the number of "Yes" responses, as studies scoring 7–8 were considered having low risk of bias, 4–6 moderate risk, and ≤ 3 as having high risk. Inter-reviewer agreement was substantial (Cohen's $\kappa = 0.86$). Furthermore, any disagreements or discrepancies were resolved through discussion, with arbitration by a third reviewer (SS or MT) when necessary.

Results

Study selection

The search through four databases and concerned literature identified 175 articles; out of which 59 articles were ex-

cluded being outside the scope of this review, thus a total of 116 articles were selected based on screening of the titles and abstracts. Further, 49 duplicate and review articles were excluded from the sample data, thus 67 eligible articles were zeroed in for full text screening. As full-text versions of 12 articles were unavailable, a total of 55 articles were finally considered for the systematic review in the present study (Figure 1).

Population Characteristics

Sample Size categorization

Varied sample sizes were used by different researchers for their studies and categorized the study population into male and female categories; though some researchers did not mention the sex category in their sample size (see Table S1 for all the articles). Among the 55 studies included in the systematic review, only 12 studies stratified the samples into distinct age-groups to evaluate age-related variations in the mandibular parameters. Further, several other studies stated that mandibular morphology changed with the progression of age and emphasized that age-based categorization has the potential to improve the accuracy and interpretability of the mandibular parameters, even if they did not formally apply the age stratification in their analyses (Arthanari et al., 2024). Out of 55 studies included in this article, 38 authors mentioned the sex and/or age of the individuals of the sample size used by them. The age-group categories used were sub-adults, adults, children and old individuals.

Imaging Modalities Employed

Among the 55 studies, OPGs were used by 38 researchers, 12 studies utilized CBCT/CT scans whereas only 4 authors

reported use of cephalometric scans for recording the mandibular parameters/dimensions in their research work; only a study used both OPG and cephalometric scans for a comparative analysis of two modalities in forensic sex estimation (see Table S1). In Figure 2a, the number of articles/publications using each modality

(CT, MCT: multi-slice computed tomography, CBCT, are shown. Researchers used either 2D or 3D radiological modality for measuring different mandibular parameters; the former includes cephalometric scans, orthopantograms whereas CBCT scans were used as a 3D modality.

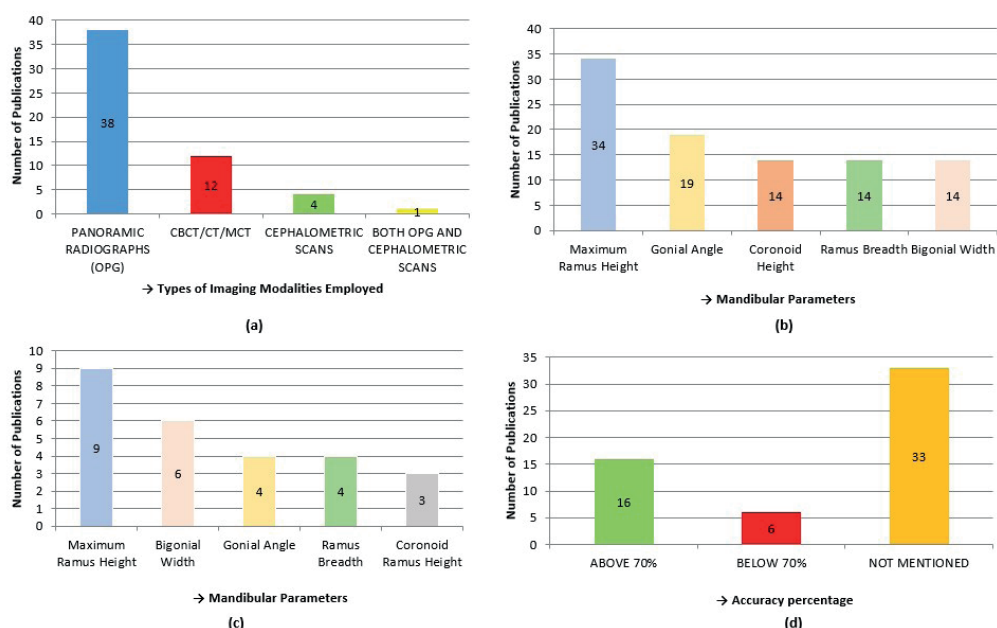


Figure 2. Graphical representation of the number of publications using different types of radiographic modalities (a), the reliability of mandibular parameters for sex (b) and age (c) estimation, and accuracy percentages of sex and/or age estimation, as reported in the different studies considered in our review. CT: Computed Tomography, MCT: Multi-slice Computed Tomography, CBCT: Cone Beam Computed Tomography.

Determination Factor (Estimation of Age, Sex or Both)

The recorded mandibular parameters were used either to estimate sex ($n=33$) (e.g., Albalawi et al., 2019; Arthanari et al., 2022; Arthanari et al., 2024; Chandrasekhar et al., 2021; Esfehiani et al., 2023; Indira et al., 2012; Kallalli

et al., 2016; Kumar et al., 2016) or age ($n=1$) (Ayesha et al., 2022) of the studied individuals based on their radiographs or CBCT scans; though some studies estimated both the age and sex ($n=21$) (e.g., Abd Elsalam et al., 2019; Arthanari et al., 2024; Behl et al., 2020; Chole et al., 2013; Garg et al., 2021;

Ulusoy and Ozkara et al., 2022) of an individual (see Table S1 for all the articles). The most commonly utilized parameters were the ramus height, gonial angle, ramus breadth, bigonial width, coronoid ramus height and condylar ramus height. Sex estimation was attempted by most of the authors. Sex estimation can be considered as the most crucial component of biological profile reconstruction as the other components are generally sex-dependent (Sehrawat, 2018). Though age estimation is most warranted in medico-legal death investigations, it is considered as the most challenging component of biological profile (Bailey & Vidoli, 2023) and our review revealed that age estimation was the least studied component of biological profile based on the mandibular radiographic measurements.

Reliable mandibular parameters for Sex Estimation

Various mandibular parameters considered by different researchers for forensic anthropological purposes are summarized in Table 1. The majority of studies (N=34) found maximum ramus height as the most reliable mandibular parameter for sex estimation (e.g., Chalkoo et al., 2019; Dhaka et al., 2015; İlgüy et al., 2014) followed by the gonial angle as reported in 19 studies (e.g., Leversha et al., 2016; Sairam et al., 2018; Vora & Arthanari, 2022), the coronoid height was reported by 14 studies (e.g., Garg et al., 2021; Kallalli et al., 2016), and ramus breadth and bigonial breadth were also reported as reliable parameters in 14 studies (e.g., Ayesha et al., 2022; Kanya et al., 2017; Ulusoy and Ozkara, 2022) (Figure 2b).

Table 1. Measurements of mandibular parameters mentioned in the studies included in this review

S. No.	Measurement (Abbreviation)	Definition	Alternative name
1.	Gonial angle (GA)	Line is traced tangent to lower mandibular border and distal border line of the ramus on each side. Mandibular angle: intersection of these lines.	Gonion angle, Mandibular angle; Ramal angle, Mandibular Gonial angle
2.	Maximum ramus height / ramus height (MRH/RH)	Ramus height most superiorly (mandibular condyle) to the tubercle, or most inferior ramus border.	Condylar Height, Condylar Ramus Height
3.	Bigonial width (BGW)	Distance between Gonian (Go) points which are inferior, posterior, and lateral points on the external mandibular angle.	Intergonial Width
4.	Antegonial angle (Ant. A)	Two lines parallel to the antegonial region until they converge at the deepest point of the antegonial notch.	Antegonial Notch Angle
5.	Mandibular foramen (MF)	Measurement in three dimensions: superioinferior (X1) (vertical distance from lowest mandibular notch point to foramen), posterioanterior (X2) (distance from foramen to a perpendicular line from mental foramen to posterior ramus border), and anterioposterior (X3) (from foramen to anterior ramus).	Inferior Alveolar Foramen
6.	Mandibular Canal (MdC)	Vertical distance from inferior cortical image of mandibular canal to inferior mandible border.	Inferior Alveolar (nerve) Canal

S. No.	Measurement (Abbreviation)	Definition	Alternative name
7.	Mental foramen (MF)	Tangent along lower mandibular body border and perpendicular line from the lowest mental foramen outline to this tangent. The distance from mental foramen to the point where the perpendicular line intersects the tangent is then measured.	Mental Nerve Foramen
8.	Maximum ramus breadth (MRB)	Distance between mandibular ramus anterior and a line joining posterior condyle and jaw angle.	–
9.	Minimum ramus breadth (mRB)	Smallest ramus diameter in the anterior–posterior plane.	–
10.	Bi-condylar width (BCW)	Distance between lateral condyle points.	Bicondylar Breadth, Intercondylar Distance
11.	Bi-mental width (BiMW)	Distance between both mental foramina.	–
12.	Projective height of ramus (PRH)	Projective ramus height measured as the vertical distance from the highest point of the mandibular condyle to the inferior border of the ramus.	–
13.	Coronoid height (CrH)	Linear distance from the coronion to the inferior border of the mandibular ramus.	Coronoid Process Height
14.	Antegonial depth (Ant. D)	Perpendicular distance from the deepest point of the antegonial notch to a tangent drawn along the inferior border of the mandible.	Gonial Depth
15.	Ramal notch depth (RND)	Linear distance from the ramus tangent line to the deepest point of the ramus notch concavity.	Sigmoid Notch Depth
16.	Cortical bone thickness (CBT)	Thickness of the radiopaque band measured at the point on the inferior border of the mandibular body corresponding to the mesial origin of the antegonial notch.	Cortical Width
17.	Mental index (MI)	Mandibular cortical width at the mental foramen	–
18.	Condylar Width (CW)	Linear distance between the most lateral point of the lateral pole and the most medial point of the medial pole on the axial section.	Glenoid Fossa Width
19.	Condylar length (CL)	Linear distance from the most posterior point of the condyle to the most anterior point of the condylar head on the axial section.	–
20.	Coronoid ramus height (CoRH)	Distance from the coronion to the point of intersection at the gonion.	Coronoid Process Height, Coronoid Height
21.	Mandibular index (MdI)	Mandibular length $\times$ 100/Bi-condylar breadth	–
22.	Mandibular body height (MBH)	Direct vertical distance from the alveolar process to the inferior mandibular border, taken perpendicular to the base at the level of the mental foramen.	–

S. No.	Measurement (Abbreviation)	Definition	Alternative name
23.	Mandibular length (ML)	Distance from the central point of the symphysis region to the most inferior point of the mandibular angle, taken along a projected straight line aligned with the posterior border.	Length of Corpus
24.	Bi-condylar length (BCL)	Straight-line distance between the most lateral points of the two condyles.	–
25.	Bi-mental breadth (BMW)	Distance between inner borders of two mental foramina.	–
26.	Bi-coronoid breadth (BiCRW)	Linear distance between the most lateral points of the right and left coronoid processes. Bigonial width defined as the distance between the most lateral points of both gonion.	–
27.	Gonial height (GH)	Linear distance from the right gonion to the menton.	–
28.	Mental foramina breadth (MFB)	Straight-line distance between mental foramina.	–

Reliable mandibular parameters for Age Estimation

Out of the 55 studies, nine researchers found maximum ramus height as the most reliable mandibular parameter for age estimation (e.g., Arthanari et al., 2024; Ayesha et al., 2022) followed by bigonial width reported in six studies (e.g., Muskaan and Sarkar, 2015; Ulu-soy & Ozkara, 2022). Four studies reported gonial angle and ramus breadth (e.g., Garg et al., 2021; Shah et al., 2020) while three studies mentioned coronoid ramus height as the reliable age estimation parameter (e.g., Behl et al., 2020) (Figure 2c).

Accuracy Percentages

The accuracy percentage of any method or technique reflects its reliability, validity and efficiency, its target users and the readers interested in findings of its application. Among the studies selected for this review, the accuracy percentage was mentioned only in 22 studies out of which only six studies reported accuracy

percentage from radiological mandibular parameters below 70%, and only 16 studies mentioned accuracy percentage of more than 70% (Figure 2d).

Methodological Quality assessment

The majority of studies included in this review showed low to moderate risk of bias, indicating an acceptable methodological quality for conducting a qualitative synthesis (Figure 3, Table S1). Twenty-two studies were found having a low risk of bias, while other 33 studies fell into a moderate risk zone; no study was classified with a high risk of bias. Notably, among the studies classified as having low risk of bias, eight studies demonstrated significantly strong methodological rigor, and no major methodological concerns were identified during the appraisal process. Although the majority of studies demonstrated a moderate methodological quality, several methodological limitations were observed across the included studies.

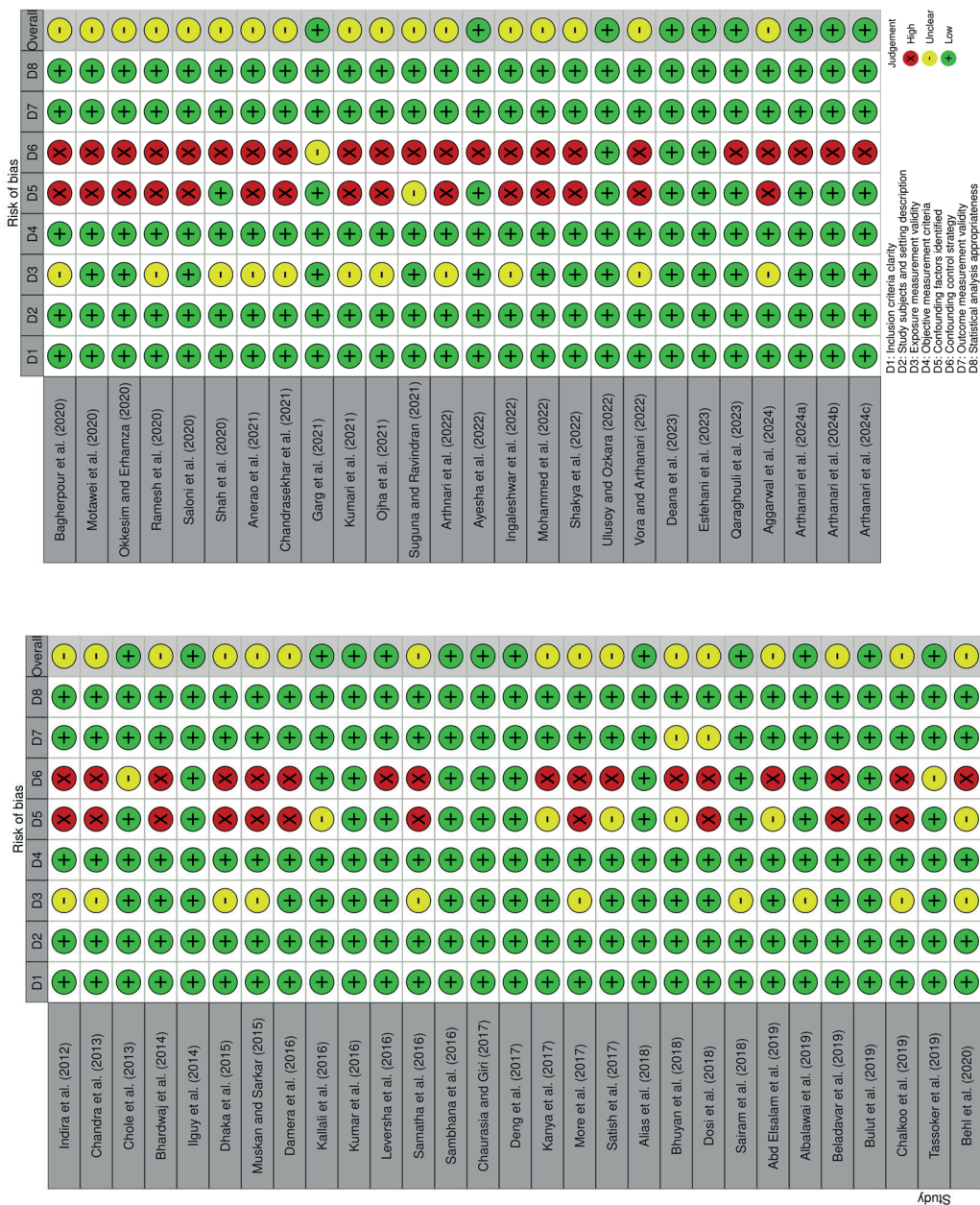


Figure 3. Traffic-light plot summarizing the risk-of-bias assessment of the included studies based on the Joanna Briggs Institute (JBI) Critical Appraisal Checklist. Each domain was evaluated as low risk (green), high risk (red), or unclear risk (yellow). The figure was generated using the ROBVIS visualization tool.

Many studies did not report any intra-observer or inter-observer reliability testing, resulting in unclear ratings for the measurement reliability domain (e.g., Arthanari et al., 2022; Behl et al., 2020; Chandra et al., 2013; Chandrasekhar et al., 2021; Sairam et al., 2018; Samatha et al., 2016). Furthermore, potential confounding factors such as age distribution, skeletal variation, population affinity, nutritional status, and dental status were rarely identified or statistically controlled in most of the studies included in the systematic review (e.g., sArthanari et al., 2024; Ayesha et al., 2022; Dhaka et al., 2015; Kanya et al., 2017; Qaraghoulis et al., 2023; Saloni et al., 2020). Most studies relied primarily on basic statistical comparisons such as t-tests or ANOVA; without giving any due consideration to multivariate regression or adjustments for the confounding factors. The generalization of the results (as extracted from the considered studies) was limited due to small sample sizes, convenience sampling, or the use of limited predictive modeling employed by some studies (e.g., Aggarwal et al., 2024; Alias et al., 2018; Beladavar et al., 2019; Kanya et al., 2017; Leversha et al., 2016; Ojha et al., 2021).

The detailed risk of bias assessment for all considered studies using the JBI Critical Appraisal Checklist is presented in Table S2. Moreover, a domain level risk of bias assessment for the included studies is illustrated in Figure 3, which represents a traffic-light plot generated using the ROBVIS visualization tool (McGuinness & Higgins, 2021).

Discussion

Forensic anthropologists use a multitude of methods and techniques for the most efficient and objective identification

pursuits of unknown human remains retrieved from different forensic contexts (Sehrawat, 2018). The primary responsibility of forensic experts is to estimate sex of the unknowns for establishing a biological profile, particularly during disaster victim identification and in medico-legal contexts. When evaluating other aspects of biological profile, like estimating age, stature and population affinity, sex determination becomes indispensable as it just halves the search process. In instances where skeletal remains are either incomplete, decomposed, or heavily damaged, the mandible proves to be an important craniofacial skeletal element as it is the largest and sturdiest facial bone. The distinctly sexually dimorphic nature of mandible (evident in its growth, size, and masticatory modelling) makes it even more important (Esfehani et al., 2023; Kumar et al., 2016; Qaraghoulis et al., 2023). Thus, mandibular parameters may be useful for biological profiling of heavily damaged, burnt or fragmented human remains (Saini et al., 2011).

Systematic reviews objectively evaluate methodologies, sample sizes, accuracy, reliability and validity of results mentioned by different articles to report the research status and future trends on the topic. Such reviews may help forensic anthropologists to stay updated on the latest developments in the field, evaluate methodological quality and rigor of different studies (Franco et al., 2025). In the present study, the literature search was conducted across four research databases identifying 55 full-text articles for final evaluation and systematic review based on the adopted inclusion and exclusion criteria. The identified studies followed varied methods, primarily involving radiological imaging modalities such as OPGs, CBCT and sometimes magnetic

resonance imaging. Orthopantograms were used in the majority of studies because of their non-invasive nature, accessibility, comprehensive coverage of the maxillofacial complex, accuracy and reproducibility of linear and angular measurements, highlighting their practical advantages for extracting the mandibular features (Arthanari et al., 2024; Saloni et al., 2020; Sambhana et al., 2016). Additionally, OPGs avoid issues related to overlapping images, and the enhancement of contrast and brightness, along with the enlargement of images, and enable accurate and consistent measurement of selected landmarks. However, OPGs may lack the spatial accuracy needed for detailed analysis of complex anatomical structures. Cone beam computed tomographs/CT scans were used by comparatively fewer number of studies, though such analysis has superior 3D reconstruction capability and detailed multi-planar visualization, which contributes to enhanced measurement precision and overall identification accuracy of this modality (Abd Elsalam et al., 2019; Arthanari et al., 2024; Saloni et al., 2020). Furthermore, discriminant function analysis was found to be the most critical statistical method used for determining sex-based metric factors and establishing sex-specific equations derived from mandibular measurements (Arthanari et al., 2024; Bagherpour et al., 2020; Damera et al., 2016; Qaraghoul et al., 2023; Saloni et al., 2020).

The application of both 2D and 3D imaging modalities demonstrated very distinct and complementary advantages in the measurement of mandibular parameters for forensic and clinical purposes. While 2D modalities, like panoramic radiographs, provide a comprehensive overview of the mandible and facilitate

measurements of linear and angular dimensions, they lack the precision required for detailed analysis of complex anatomical structures (Arthanari et al., 2024). A significant number of studies used 2D panoramic radiographs in their methodology due to their wider availability, cost-effectiveness, and low radiation exposure (Chandra et al., 2013; Indira et al., 2012; Leversha et al., 2016). Panoramic radiography, being a curved-plane tomographic technique, allows for broader anatomical coverage, thus facilitating the measurement of key mandibular landmarks. More advanced 3D imaging modalities such as CBCT, CT, or MCT offer high-resolution volumetric imaging, allowing precise measurement of anatomical landmarks and better visualization of the bone density and its morphology (Anerao et al., 2021; Deng et al., 2017; Jambunath et al., 2016), though very few studies included in our review employed these advanced techniques for measuring mandibular dimensions. Cone beam computed tomography has demonstrated superior accuracy in measuring mandibular length, ramus height, and gonial angle-the critical parameters used for sex and age estimations. While 2D modalities are beneficial for quick assessments and broader accessibility, 3D imaging is essential in cases where higher precision is required. However, the integration of 2D and 3D imaging modalities enhances accuracy, reliability, and scope of mandibular morphometric analysis for forensic anthropological purposes.

The studies presenting higher accuracy ranges between 76% and more than 90% demonstrated substantial variability, reportedly imprinted by the population-specific characteristics, imaging modality used, and the number of variables considered, and these features were part of the

particular studies. While CBCT- and 3D CT-based studies showed higher accuracy levels (ranging above 84%), some authors reported discriminant rates exceeding the 95% mark in males and 100% in females, especially when the primary indicators under consideration were condylar height or combined ramus-based measurements (Abd Elsalam et al., 2019; Alias et al., 2018; Kallali et al., 2016; Shakya et al., 2022). It is pertinent to note that the variations in accuracy rates and the best sexually dimorphic parameter are often found attributed to multiple attributes such as genetics, nutritional status, environmental factors, lifestyle, and indigenous background of an individual (Saloni et al., 2020; Shakya et al., 2022).

Sexual dimorphism has been reflected in some mandibular parameters such as ramus height, gonial height, and muscular attachment sites (Arthanari et al., 2024). Morphological and developmental factors provide necessary explanation for the strong consistency exhibited by the mandibular ramus for having sexual dimorphism when compared to other mandibular regions. For instance, the presence of greater muscle mass and functionality is often associated with males, leading to increased ramus height, broader attachment sites, and more robust morphology, particularly in the coronoid and condylar processes. Additionally, hormonal influences and different rates, durations, and timings of mandibular growth in both sexes further accentuate the structural disparities (Indira et al., 2012; Shakya et al., 2022). However, as sex estimation is a population-specific aspect, existing regional discriminant functions should be regularly revised to address any biological variability across age-groups and populations (Damera et al., 2016; Sambhana et al., 2016).

Our systematic review was formulated to analyse the metrics associated with the mandible that present the greatest sexual dimorphism and help undertake the task of age estimation based on these parameters. Across all studies selected for the systematic review, which represented a variety of populations, approximately 17 articles exhibited an accuracy rate of 70% to 90%. These studies also demonstrated consistent sexual dimorphism, highlighting the medium- to high-grade discriminatory power of various radiological modalities used for mandibular measurements. Furthermore, while most of the studies reported several methodological differences, there was a remarkable consistency in the parameters selected. Among all the parameters evaluated, few of them were found associated with the greatest morphological changes and the most dimorphic portions of the mandible; making the measurements substantially useful for sex determination. The mandibular parameters like ramus height, coronoid height, bigonial breadth, condylar height, inter-condylar distance, maximum and minimum ramus breadth, mandibular body height, and gonial angle were found highly reliable for sex estimation. While ramus height was consistently identified as the best discriminator for sex estimation across multiple populations and radiological modalities (Arthanari et al., 2024; Damera et al., 2016; Qaraghoulis et al., 2023; Saloni et al., 2020; Sambhana et al., 2016), the minimum ramus breadth was reported as the next best complementary variable to ramus height for the purpose (Arthanari et al., 2024; Indira et al., 2012). On the other hand, condylar height was found to be the most consistent parameter for age estimation, followed by the bigonial width as the secondary significant pa-

parameter and the mandibular length-related measurements crucially important for the population-specific assessments of unknown remains (Arthanari et al., 2024). A study presented a contradiction to other studies and reported that minimum ramus breadth had the least sexual dimorphism associated with mandibular ramus (Shakya et al., 2022).

Mandibular ramus was found to exhibit the highest degree of sexual dimorphism, making it a reliable mandibular tool for sex determination in forensic and anthropological scenarios (Kumar et al., 2016; Saloni et al., 2020; Sambhana et al., 2016). Across all radiographic studies reviewed here, consistent evidence of sexual dimorphism was reported in the ramus region, gonial region and the transverse widths of the mandible. Furthermore, the general trend observed across multiple mandibular measurements across different populations indicated that the linear dimensions of the ramus and jaw widths were statistically significantly higher in males than the females (Sambhana et al., 2016; Shakya et al., 2022). The sex estimation accuracy rates associated with mandibular parameters generally range from 71.1% to 84% among most of the studies reviewed in this study (Kumar et al., 2016; Saloni et al., 2020; Shakya et al., 2022). Also, the linear and angular measurements that performed well for discriminating between males and females, were generally found associated with overall size and robustness of the mandible; males having a larger ramus region and wider bigonial/bicondylar dimensions (Abd Elsalam et al., 2019; Alias et al., 2018; Damera et al., 2016;). Similarly, certain mandibular parameters exhibited low sexual dimorphism or negligible or statistically insignificant differences, such as

Sella-Nasion/A-point (SNAr), bi-mental breadth, mental index, etc. (Abd Elsalam et al., 2019; Bagherpour et al., 2020). Conclusively, these observations endorse the fact that the mandible, particularly its ramus and the condylar region, provides a biologically robust and globally consistent framework for sex estimation, and it also highlights the need for continued population-specific validation and methodological standardization studies.

Variability in Study Design and Methodology

The reviewed literature revealed a notable trend in variability of study design, sample size, age-groups selected, and the imaging techniques used. Some studies considered the smaller but demographically diverse populations, while others studied the larger and more heterogeneous group of individuals in their study sample. The funding opportunities, time constraints, logistical challenges, and accessibility of subjects or skeletal remains (as study material) were commonly cited as the most limiting factors for selecting the sample size. Age-group selection was considerably varied as some studies focused specifically on age-related mandibular changes, while others included the broader or undifferentiated age groups; such selections were influenced by the cultural, health, or demographic credentials of the selected population groups. Furthermore, the choice of imaging modality was largely dependent on the researchers' institutional resources, funding, expertise, and the precision required to satisfy the study objectives. Such disparities in choice of radiological modality reflected the adaptive nature of study design in forensic and anthropological research, tailored to available tools, resources, context, and research goals.

Implications for Standardization and Future Research

The diversity in research designs by different researchers underscores the urgent need for standardization of protocols to be used for evaluation of mandibular parameters towards forensic sex and age estimations. Establishing guidelines for imaging techniques, measurement protocols, and sample selection criteria will facilitate more reliable comparisons and meta-analyses in the future. Such insights can direct future research goals and funding priorities, particularly in advancing the use of radiological modalities for forensic anthropological purposes.

The variation in sample size, age-groups and techniques significantly affected the generalizability of the findings across diverse populations. Small or homogeneous samples often limit the applicability of results, making it difficult to draw valid conclusions relevantly applicable to broader demographics. Also, differences in methodologies influence the accuracy and reliability of the measurements which, in turn, impact the robustness of conclusions drawn about age and sex estimations. These variations also highlight the research trends, revealing shifts toward specific methodologies or demographic focuses that reflect changing priorities within forensic anthropology. Furthermore, the lack of uniformity in research design complicated efforts to establish standardized protocols, making it more challenging to compare results across the studies. Ultimately, addressing these variations is crucial for enhancing the credibility of findings and advancing the forensic radiological/anthropological field towards more standardized and effective identification techniques.

Risk of Bias and Quality Assessment

The methodological quality assessment undertaken using JBI Critical Appraisal Checklists indicated that most of the studies included here demonstrated a moderate to low risk of bias. It suggested that qualitative synthesis of the included studies was possible as several studies exhibited clear study designs, well-defined inclusion criteria, and used reliable radio-imaging modalities such as panoramic radiographs or CBCT for recording different mandibular measurements (Deana et al., 2023; Deng et al., 2016; Ilguy et al., 2014). Although certain limitations have been highlighted based on the overall methodological quality of the included studies; their inclusion in the qualitative synthesis remains acceptable based on the continued exploration of mandibular morphometric parameters as a predictor of sexual dimorphism in forensic anthropological identification contexts (Deana et al., 2023; Deng et al., 2016; Esfehiani et al., 2023). Although most of the studies demonstrated acceptable methodological standards; the variability in study designs and analytical approaches employed by different studies was identified across the published literature on the topic. Furthermore, it was observed that several studies relied primarily on simple comparative statistics rather than comprehensive predictive modelling, which may potentially limit the practical forensic applicability of some mandibular parameters (Aggarwal et al., 2024; Alias et al., 2018; Beladavar et al., 2019; Bhardwaj et al., 2014; Chole et al., 2013; Kanya et al., 2017; Ojha et al., 2021).

Some studies even reported inconsistencies in reporting measurement reliability and observer calibration, thereby influencing the reproducibility of mor-

phometric analyses across different populations and the imaging modalities (Aggarwal et al., 2024; Arthanari et al., 2022; Chandrasekhar et al., 2021; Indira et al., 2012; Vora and Arthanari, 2022). All of these methodological differences highlight the need for greater standardization in the protocols associated with mandibular parameters by strengthening the reliability assessment, sampling strategies employed, and the statistical validation of predictive models which, in turn, may improve the robustness of the resultant observations (Damera et al., 2016; Kallali et al., 2016). Nevertheless, the presence of a significant number of methodologically robust studies may strengthen the evidentiary value of the method or technique, required for enhanced credibility of the mandibular measurements as potential forensic indicators of sex, age or both (Aggarwal et al., 2024; Arthanari et al., 2022). Thus, future research endeavors should focus on employing larger, population-specific datasets and validating the multivariate models that may further improve the forensic applicability of these morphometric approaches.

Limitations of this Systematic Review

Though the present review provides a detailed overview of methodologies and techniques used for radiological mandibular parameters for forensic sex and/or age estimation, still there are certain limitations of this study. Firstly, publication bias analysis, such as funnel plot asymmetry and Egger's regression, was not chosen as an analytical tool due to the insufficient number of studies eligible for each comparison in this review, which precluded a meaningful assessment. These publication bias methods necessitate the requirement of minimum 10 studies per quantitative procedure for

accurate statistical power and interpretations (Duval & Tweedi, 2000; Egger et al., 1997; Sterne et al., 2000, 2011). In this study, various outcome types were analysed, including sex estimation parameters, age estimation parameters, and the presence of any modality-specific subgroups; however, none of them met the required threshold values. To prevent the generation of misleading patterns or unreliable estimates, publication bias analysis was excluded from the current review study. Also, non-English studies were not considered in this review, resulting in the exclusion of vast data from around the world for valid generalization and conclusions. The present study does not discuss the current challenges for measuring mandibular parameters through different radiological modalities such as differences in measuring techniques and the results due to advancement and easy accessibility of modalities like CBCT scans. If above limitations or challenges can be overcome, one can suggest a standardized methodology for effective forensic identification strategy to be used in the criminal justice system. Mandibular parameters exhibited notable variations among two sexes and different age-groups of various population groups and it may pose another limitation towards accurate assessments or generalization of mandibular morphology or its dimensions for forensic purpose. Thus, careful considerations and new investigations will address the impact of such variation in the future (Arthanari et al., 2024).

Gonial and antegonial angles have defined limits, though they can serve as useful supplementary indicators for sex estimation of unknown mandibles. While assessing these angles, forensic anthropologists and orthodontists must exercise caution and consider them within

the context of a comprehensive analysis that includes demographic information and various skeletal indicators. To enhance the accuracy and reliability of sex determination using these angles, further research is needed to standardize the measurement techniques and validate them for diverse populations (Arthanari et al., 2024).

Relying solely on mandibular characteristics for age estimation has its limitations; the factors like population variations, sex differences, inter/intra-observer variability, and taphonomic changes may add to these challenges. To enhance the accuracy and reliability of forensic age estimations, forensic anthropologists often recommend utilizing multiple skeletal indicators to mitigate these challenges or limitations (Arthanari et al., 2024). Chandra et al. (2013) reported that larger study samples and a thorough assessment of additional parameters related to the mental foramen are needed to validate the study findings. The high radiation exposure associated with CBCT modality is a serious limitation, though it provides precise results. Most of the mandibular parameter assessment studies are based on the radiological examination of subjects visiting the dental outpatient department of a hospital for different reasons, thus the results obtained cannot be generalized to the entire population group (Ramesh et al., 2020; Shakya et al., 2022).

Conclusions

The present systematic review revealed that the majority of included studies (60%) considered mandibular radiometric dimensions for sex estimation and about 38% estimated both sex and age from these parameters. Fewer than half

of the studies reported accuracy percentages of their findings, and the reported accuracy percentage of most studies was much below the acceptable forensic thresholds. The review also highlighted that by surmounting the reported limitations, there may be a more nuanced understanding of contributions of mandibular shape, size and morphology for forensic anthropological sex and age estimations. Our results clearly reflected that sex and age estimation should not be solely relied upon mandibular measurements only, and these observations are expected to provide directional insights to future forensic anthropologists that mandibular morphometric analyses should be attempted in conjunction with other reliable methods towards human identification for medico-legal purposes.

Additional information

Supplementary materials [online version].

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Author contributions

JSS conceptualized the topic, framed the outline of the manuscript, scrutinized the available literature, wrote the

final manuscript and revised its final version, SS conducted pilot survey of the literature, suggested research trends and preliminary draft of the manuscript, ST helped in literature search and systematic review, drawing figures and revising the manuscript, MT provided valuable clinical inputs, revised and edited the manuscript. All authors read and agreed to the revised version of the manuscript.

Ethics statement

Not applicable.

Data availability statement

The reviewed articles are listed in supplementary materials.

Financial disclosure

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Conflict of interest

None to declare.

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SUPPLEMENTARY MATERIALS

Research dynamics in the applicability of radiological mandibular parameters for forensic sex and age estimation: A systematic review

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Table S1. Studies included in the systematic review.

Author (Year)	Country	Sample size	Age group (years)	Outcome type	Radiological modality used	Parameters assessed	Accuracy Percentage	Major Outcomes
Indira et al. (2012)	India	100 (50 M, 50 F)	20-50	Sex	Panoramic Radiographs (OPGs)	Ramus Breadth, Condylar Height, Projective Height of Ramus, and Coronoid Height	76%	Mandibular ramus identified as the best sex predictor.
Chandra et al. (2013)	India	100	18-62	Sex	Panoramic Radiographs (OPGs)	Mental Foramen	Not mentioned	Males showed significantly higher average values for both the superior and inferior distances from the mental foramen to the lower mandibular border.
Chole et al. (2013)	India	1060 (566 M, 494 F)	15 to 66+	Both Sex & Age	Panoramic Radiographs (OPGs)	Gonial angle, Antegonial angle, Antegonial Depth	Not mentioned	Ant. A, Ant. D, GA showed no significant correlation with age but differed significantly between sexes.
Bharadwaj et al. (2014)	India	300 (150 M, 150 F)	25-54	Both Sex & Age	Panoramic Radiographs (OPGs)	Gonial Angle, Antegonial Angle, Mental Foramen, Mandibular Canal, Mandibular Foramen.	Not mentioned	Ant. A, Ant. D, GA showed no significant correlation with age but differed significantly between sexes. While sex-based comparison of GA, Ant. A, mandibular canal and mandibular foramen showed statistically significant differences. Among all parameters, changes in the mandibular canal and mandibular foramen were most significant with advancing age.
İlgüy et al. (2014)	European descent	161 (66 M, 95 F)	18-85	Sex	CBCT	Foramen magnum, Gonial angle, Ramus length, Minimum Ramus Breadth, Mandibular Base Length, Bigonial Breadth, Bicondylar Breadth	83.2%	The study identified GA, RL, MBL, BGW as the final predictors of sex.

Author (Year)	Country	Sample size	Age group (years)	Outcome type	Radiological modality used	Parameters assessed	Accuracy Percentage	Major Outcomes
Dhaka et al. (2015)	India	90 (52 F, 38 M)	8-20	Both Sex & Age	Lateral Cephalogram	Mandibular Body Length, Mandibular Length, Mandibular Height	Not mentioned	The study found no significant age-related increase in gonial angle, though females had larger angles. A significant increase in mandibular length (Gn to Go) was observed in females aged 8–12 years, indicating peak growth during this period.
Muskaan and Sarkar (2015)	India	40	21-60	Both Sex & Age	Panoramic Radiographs (OPGs)	Mental Index, Maximum Ramus Breadth, Minimum Ramus Breadth, Coronoid Height	Not mentioned	MI and CrH showed significant differences for both age and sex, while MRB was significantly different between sexes.
Damera et al. (2016)	India	80	20-50	Sex	Panoramic Radiographs (OPGs)	Maximum Ramus Breadth, Minimum Ramus Width, Maximum Condylar Height, Maximum Height of Ramus, Gonial Angle, Bigonial Width	83%	The greatest sexual dimorphism was observed in the CH.
Kallali et al. (2016)	India	30 (15 M, 15 F)	10-60	Sex	3D CT	Gonial angle, Ramus length, Minimal Ramus Breadth, Coronoid Height, Gonion Gnathion Length, Bicondylar Breadth, Bigonial Length	76%	The study found that five out of seven parameters – GA, RL, mRB, CrH, – showed significant differences ($P < 0.05$), with an overall accuracy of 86% for males and 82% for females.
Kumar et al. (2016)	India	308 (154 M, 154 F)	20-69	Sex	Panoramic Radiographs (OPGs)	Bi-condylar Width, Bi-gonial Width, Bi-mental Width, Maximum Ramus Breadth, Minimum Ramus Breadth	71.1%	BCW, BGW, MFW, MRB, and mRB showed statistically significant differences, indicating clear sexual dimorphism and their usefulness in sex determination.
Leversha et al. (2016)	Australia	220	19-69	Both Sex & Age	Panoramic Radiographs (OPGs)	Gonial Angle, Bigonial Width, Ramus height	Not mentioned	Males had statistically significantly larger RH and BGW than females, whereas females had significantly larger gonial angles than males.

Samatha et al. (2016)	India	120 (60 M, 60F)	18-45	Sex	Panoramic Radiographs (OPGs)	Maximum Ramus Breadth, Minimum Ramus Breadth, Condylar Height/Maximum Ramus Height, Projective Height of Ramus, Coronoid Height	Not mentioned	P < 0.05 for MRB, CH, PRH.
Sambhana et al. (2016)	India	384 (192 M, 192 F)	7-75	Sex	Panoramic Radiographs (OPGs)	Minimum Ramus Breadth, Maximum Ramus Breadth, Mandibular Length, Bicondylar Breadth, Mandibular Index, Ramus Height, Mandibular Body Height, Gonial Angle, Bigonial Width, Coronoid Height	75.8%	CrH was the single best parameter indicating sexual dimorphism.
Chaurasia and Giri (2017)	India	150	20-30	Age, Sex	CBCT	Condylar Height, Condylar Width, Condylar Length	Not mentioned	Condylar width showed statistically significant differences in values for both age and sex.
Deng et al. (2017)	China	219 (111 M, 108 F)	23-63	Sex	CBCT Scan	Bi-condylar Breadth, Bigonial Breadth, Antegonial Notch Breadth, Mental Foramina Breadth	Not mentioned	All the described breadth dimensions were sexually dimorphic, significantly larger in males than in females.
Kanya et al. (2017)	Indonesia	200 (100 M, 100 F)	14-35	Sex	Panoramic Radiographs (OPGs)	Ramus Height, Gonial Angle, Bigonial Width, Condylar Ramus Height, Coronoid Ramus Height, Maximum Ramus Breadth, Minimum Ramus Breadth, Mental Index	Not mentioned	Mandibular parameter values were generally higher in males than females, except for GA. Statistically significant differences were noted in RH, BGW, CRH, CoRH, MRB and mRB in both the sexes.

Author (Year)	Country	Sample size	Age group (years)	Outcome type	Radiological modality used	Parameters assessed	Accuracy Percentage	Major Outcomes
More et al. (2017)	India	1000 (500 M, 500 F)	21-60	Sex	Panoramic Radiographs (OPGs)	Maximum Ramus Breadth, Minimum Ramus Breadth, Condylar Height, Projective Height of Ramus, Coronoid Height	69%	Mean dimensions of all ramus parameters statistically significant and higher in males. Mean MRB and mRB were 27.44 ± 3.41 mm and 32.27 ± 3.40 mm, respectively. CH and PRH measured 71.78 ± 5.98 mm and 65.62 ± 6.19 mm, while CrH was 59.23 ± 6.08 mm. A significant correlation was observed between sex and mandibular ramus morphology ($p < 0.05$).
Satish et al. (2017)	India	200 (100 M, 100 F)	18-30	Sex	Panoramic Radiographs (OPGs)	Maximum Ramus Height, Bigonial Width, Bicondylar Breadth	Not men- tioned	CH proved to be the most dimorphic parameter
Alias et al. (2018)	Malaysia	79 (48 M, 31 F)	18-74	Sex	PMCT	Maximum Ramus Breadth, Minimum Ramus Breadth, Condylar Height, Maximum Ramus Height, Coronoid Height, Mandibular Height, Symphyseal Height, Bigonial Breadth, Bicondylar Breadth	78.5%	All parameters significantly greater in males vs. females ($p < 0.01$). Statistically significant differences in BGW and CH between the sexes.
Bhuyan et al. (2018) [49]	India	50 (25 M, 25 F)	11-79	Age, Sex	Panoramic Radiographs (OPGs)	Ramus Width, Maximum Ramus Breadth, Minimum Ramus Breadth, Condylar Height, Projective Height of Ramus, Coronoid Height, Gonial Angle, Bigonial Width	Not men- tioned	A statistically significant sex difference was observed for GA, RH, and BGW. All parameters increased with age, with significant differences on the right side for GA and RH.

Dosi et al. (2018)	India	545	20-90	Age, Sex	Panoramic Radiographs (OPGs)	Mental Foramen, Ramus Height	Not mentioned	Statistically significant results were obtained for Mental foramen and RH with age and sex..
Sairam et al. (2018)	India	150	Any age group	Age, Sex	Panoramic Radiographs (OPGs)	Gonial Angle, Ramus Height, Condylar Height, Ramal Notch Depth, Cortical Bone Thickness	Not mentioned	When sex alone was assessed, significant differences were observed for GA (Lt side), RH, condylar length, and RND (Rt side) and cortical bone thickness on both sides. Cortical bone thickness and condylar length also showed significant differences with age.
Abd El-salam et al. (2019)	Egypt	102 (51 M, 51 F)	20-50	Age, Sex	CBCT Scan	Gonial Angle, Bimental Breadth, Bigonial Width, Bicondylar Breadth, Bicoronioid breadth, Mental Index, Height of Mandible from Mental Foramen, Maximum Mandibular Length, Mandibular Index	M = 83.7%; F = 81.3%	The study showed a statistically significant difference ($P < 0.05$) in right GA, right MI, right and left MH from the mental foramen, BGW, BCW, BiCrW, maximum mandibular length, and mandibular index.
Albalawai et al. (2019)	Saudi Arabia	200	18-60	Sex	CBCT Scan	Gonial Angle, Gonial Height, Bigonial Width	67%,	Sex predicted using these parameters ($P < 0.0001$).
Belaldavar et al. (2019)	India	304 (149 M, 155 F)	18-30	Sex	Lateral Cephalogram	Gonial Angle	56.3%	Mean GA of 122.7° in females and 121.1° in males was statistically significant with females having larger GA as vs. males.
Bulut et al. (2019)	Turkey	300 (150 M, 150 F)	20-80	Sex	CT Scan	Gonial Angle	Not mentioned	Males had slightly smaller GA values than females across all age groups (I, II, and III). No significant sex difference was observed in groups I and II, while a statistically significant difference ($P < 0.05$) was noted in group III.
Chalkoo et al. (2019)	India	80 (40M, 40F)	18-50	Sex	Panoramic Radiographs (OPGs)	Ramus Breadth, Condylar Height, Projective Ramus Height, Coronoid Height	Not mentioned	Sexual dimorphism was statistically significant for CrH, CH, and PRH.

Author (Year)	Country	Sample size	Age group (years)	Outcome type	Radiological modality used	Parameters assessed	Accuracy Percentage	Major Outcomes
Tassoker et al. (2019)	Turkey	121 (50 M, 71 F)	10-69	Age, Sex	CBCT Scan	Gonial Angle, Ramus Length, Maximum Ramus Breadth, Minimum Ramus Breadth, Bignial Width	Not men- tioned	Statistically significant differences between mandibular measurements from CBCT and PR scans; PR showed comparatively higher values.
Behl et al. (2020)	India	400 (200 M, 200 F)	10-40	Age, Sex	Panoramic Radiographs (OPGs)	Ramus Breadth, Condylar Ramus Height, Coronoid Ramus Height, Gonial Angle	Not men- tioned	Males showed increased value for RB, CRH, CoRH. Age and ramus linear measurements were significantly and positively correlated.
Bagher- pour et al. (2020)	Iran	202 (101 M, 101 F)	18-50	Sex	Lateral Cep- halogram	Nasion, Anterior Nasal Spine, Posterior Nasal Spine, Menton, Infradental, Articular, Gonion, Condylion, Gnathion, Mandibular Ramus Height	87.6%	Based on the analyses, facial height (NMe), MRH, mandibular plane (MeGo), and frontal sinus width (Fswd) were the most significant contributors to sexual dimorphism among the selected parameters.
Motawei et al. (2020)	Egypt	213 (99 M, 114 F)	7-58	Age, Sex	CBCT Scan	Ramus Length	67%	Mean length of mandible ramus differed significantly between males and females.
Okkesim and Er- hamza (2020)	Turkey	70 (35 M, 35 F)	Not men- tioned	Sex	CBCT Scan	Coronoid Height, Condylar Height, Mandibular Ramus Height, Minimum Ramus Breadth,	Not men- tioned	All ramus parameters from CBCT differed statistically between the sexes ($P < 0.05$).
Ramesh et al. (2020)	India	150	20-70	Age, Sex	Panoramic Radiographs (OPGs)	Condylar Ramus Height, Coronoid Ramus Height	Not men- tioned	CRH and CoRH values were significantly higher in males than females and also showed significant differences with age.

Saloni et al. (2020)	India	200	21-70	Sex	Panoramic Radiographs (OPGs)	Maximum Ramus Breadth, Minimum Ramus Breadth, Coronoid Height, Condylar/ Maximum Ramus Height, Projective Ramus Height	77.6%	Mean mRB, MRH, and PRH significantly higher among males, while MRB slightly higher in females.
Shah et al. (2020)	India	300 (150 M, 150 F)	10-69	Age, Sex	Panoramic Radiographs (OPGs)	Gonial Angle, Ramus Height, Bigonial Width	Not mentioned	Statistically significant age-related differences were observed in GA dimensions. For sex, GA, RH and BGW showed highly significant differences.
Anerao et al. (2021)	India	100 (50 M, 50 F)	20-69	Age, Sex	Panoramic Radiographs (OPGs)	Mandibular Body Height, Mental Foramen to Mandibular Distance, Mandibular Ramus Height, Mandibular Ramus Height	Not mentioned	The overall mean values of D1, D2, D3, and D4 were significantly higher in males across all age groups, with D4 showing a particularly high level of significance.
Chan-drsekhar et al. (2021)	India	80	10-35	Sex	Lateral Cephalogram	Total Mandibular Body Length, Mandibular Length, Mandibular Height, Gonial Angle	Not mentioned	Statistically significant sex differences were observed for the ML, MH, and the age of the study participants ($p < 0.05$).
Garg et al. (2021)	Malaysia	180	21-60	Age, Sex	Panoramic Radiographs (OPGs)	Ramus Breadth, Height of Coronoid Process, Mental Index	Not mentioned	MRB showed significant differences for ethnic determination whereas MRB showed significant differences for age estimation. CrH and MRB showed statistically significant result between male and female.
Kumari et al. (2021)	India	50 (25 M, 25 F)	20-40	Sex	Panoramic Radiographs (OPGs)	Condylar Height, Coronoid Height, Gonial angle	Not mentioned	CH and CrH on both right and left sides were significantly higher in males than females. Although GA values were higher in males, the differences between sex were not statistically significant. All three variables showed higher mean values in males.

Author (Year)	Country	Sample size	Age group (years)	Outcome type	Radiological modality used	Parameters assessed	Accuracy Percentage	Major Outcomes
Ojha et al. (2021)	Nepal	216	17-39	Sex	Panoramic Radiographs (OPGs)	Condylar Height, Coronoid Height, Projective Height of Ramus, Maximum Ramus Breadth, Gonial Angle, In- tergonial Width	63.4%	The vertical parameters were found to be greater in males than in females. CrH was the most dimorphic param- eter in discriminant analysis.
Suguna and Ravindran (2021)	India	100 (37 M, 63 F)	14-35	Age, Sex	Panoramic Radiographs (OPGs)	Gonial Angle, Bigonial Width, Ramus Height	Not men- tioned	Increased BGW was found in males when compared to females and the difference was found to be statistically highly significant
Arthanari (2022)	India	50 (25 M, 25 F)	51-60	Sex	Panoramic Radiographs (OPGs)	Gonial Angle	Not men- tioned	Statistically significant correlation be- tween GA of males and females was confirmed.
Ayesha et al. (2022)	India	200 (100 M, 100 F)	9-20	Age	OPGs and Lateral Cephalogram	Gonion, Gnathion, Mandibular Body Length, Mandibular Length, Mandib- ular Height	OPG = 93.8% Lateral cephalo- gram = 79.7%	RH was found to be best parameter for age estimation.
Ingalesh- war et al. (2022)	India	200 (100 M, 100 F)	18-58	Sex	Panoramic Radiographs (OPGs)	Condyle-Coronoid Angle, Gonial Angle	Not men- tioned	Significant differences in GA and CCA in both sexes with females hav- ing higher values than males.
Moham- med et al. (2022)	India	300	20-60	Sex	Panoramic Radiographs (OPGs)	Mandibular Ramus, Position of Mental Foramen, Inter- condylar Distance	Not men- tioned	10 out of 14 mandibular variables, including ramus and mental foramen measurements, showed statistically significant sexual dimorphism.
Shakya et al. (2022)	Nepal	150	18+	Sex	Panoramic Radiographs (OPGs)	Maximum Ramus Breadth, Minimum Ramus Breadth, Condylar Height/ Maximum Ramus Height, Projective Height of Ramus, Coronoid Height	84%	CH predicted sex.

Ulusoy & Ozkara (2022)	Turkey	1100 (550 M, 550 F)	3-13	Age, Sex	Panoramic Radiographs (OPGs)	Ramus Height, Condylar Ramus Height, Coronoid Ramus Width, Minimum Ramus Width, Bigonial Width, Bicondylar Width, Bimental Width, Gonial Angle	66.72%	Linear dimensions higher in males vs. females across all ages. GA did not vary by sex.
Vora and Arthanari (2022)	India	60 (30 M, 30 F)	30-35	Sex	Panoramic Radiographs (OPGs)	Mandibular Maximum Ramus Breadth	Not mentioned	There is a significant difference between RB of males and females.
Deana et al. (2023)	South America	594 (204 M, 390 F)	18-84	Sex	Panoramic Radiographs (OPGs)	Mandibular Angle, Mandibular Ramus Height, Bigonial Breadth, Condylar Coronoid Distance, Bicondylar Breadth, Distance from the Mental Foramen to Mandibular Base, Distance between Mental Foramina, Distance from the Mandibular Notch – Mandibular Lingula	Not mentioned	The best sex predictor was MRH, followed by distance from the HMF-MB and BCW.
Esfehiani et al. (2023)	Iran	290 (145 M, 145 F)	18-70	Sex	Panoramic Radiographs (OPGs)	Minimum Ramus Width, Maximum Ramus Width, Condylar Height, Coronoid Height, Antegonial Angle, Antegonial Depth, Gonial Angle, Distance between the superior border of the Mental Foramen and the inferior border of the Ramus, Distance between the inferior border of the Mental Foramen and the inferior border of the Ramus, Bicondylar Breadth, Bigonial Breadth	Not mentioned	All indices, except GA, showed significant sex differences and were useful for sex determination in the univariate model. Even after adjusting for confounders, CH, CrH, and MF-IR Dist (Sup) remained significantly greater in males ($P < 0.05$). The best model for sex estimation used BCW, CH, CrH, mRB, and superior border mental foramen. Values >56% indicated males, lower values indicated females.

Author (Year)	Country	Sample size	Age group (years)	Outcome type	Radiological modality used	Parameters assessed	Accuracy Percentage	Major Outcomes
Qaraghouli et al. (2023)	Egypt	60 (30 M, 30 F)	18 +	Sex	CBCT Scan	Coronoid Height, Mandibular Ramus Height,	84.2%	The measured variables (CrH and PRH) showed a statistically significant difference between the sexes.
Aggarwal et al. (2024)	India	90	17 -21	Sex	Panoramic Radiographs (OPGs)	Condylar Area, Condylar Perimeter, Condylar Height, Ramal Height, Ramus Tangent, Total Height	Not mentioned	CH was significantly greater in males than females.
Arthanari et al. (2024a)	India	500 (250 M, 250 F)	41-50	Age and sex	Panoramic Radiographs (OPGs)	Projective Ramus Height, Bigonial Width, Antegonial Depth, Antegonial Angle, Maximum Ramus Breadth	89.4%	BGW was preferred for age, while Ant.A for sex estimation. Age and sex estimation using these variables was achieved in this sample from India.
Arthanari et al. (2024b)	India	500 (250 M, 250 F)	20-30	Age, Sex	Panoramic Radiographs (OPGs)	Condylar Ramus Height, Minimum Ramus Breadth, Projective Ramus Height	Not mentioned	CRH suitable for age estimation, while GA, CoRH, and PRH preferable for sex estimation.
Arthanari et al. (2024c)	India	500 (250 M, 250 F)	20-30	Sex	Panoramic Radiographs (OPGs)	Gonial Angle, Antegonial Angle	Not mentioned	GA was found to be best predictor of sex.

Table S2. Risk-of-Bias assessment of included studies using the JBI Critical Appraisal Checklist.

AUTHOR (YEAR)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	TOTAL YES	RISK
Indira et al. (2012)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Chandra et al. (2013)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Chole et al. (2013)	Y	Y	Y	Y	Y	U	Y	Y	7	LOW
Bhardwaj et al. (2014)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Ilguy et al. (2014)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Dhaka et al. (2015)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Muskan and Sarkar (2015)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Damera et al. (2016)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Kallali et al. (2016)	Y	Y	Y	Y	U	Y	Y	Y	7	LOW
Kumar et al. (2016)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Leversha et al. (2016)	Y	Y	Y	Y	Y	N	Y	Y	7	LOW
Samatha et al. (2016)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Sambhana et al. (2016)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Chaurasia and Giri (2017)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Deng et al. (2017)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Kanya et al. (2017)	Y	Y	Y	Y	U	N	Y	Y	6	MODERATE
More et al. (2017)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Satish et al. (2017)	Y	Y	Y	Y	U	N	Y	Y	6	MODERATE
Alias et al. (2018)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Bhuyan et al. (2018)	Y	Y	Y	Y	U	N	U	Y	5	MODERATE
Dosi et al. (2018)	Y	Y	Y	Y	N	N	U	Y	5	MODERATE
Sairam et al. (2018)	Y	Y	U	Y	Y	Y	Y	Y	7	LOW
Abd Elsalam et al. (2019)	Y	Y	Y	Y	U	N	Y	Y	6	MODERATE
Albalawai et al. (2019)	Y	Y	U	Y	Y	Y	Y	Y	7	LOW
Beladavar et al. (2019)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Bulut et al. (2019)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Chalkoo et al. (2019)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Tassoker et al. (2019)	Y	Y	Y	Y	Y	U	Y	Y	7	LOW
Behl et al. (2020)	Y	Y	U	Y	U	N	Y	Y	5	MODERATE
Bagherpour et al. (2020)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Motawei et al. (2020)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Okkesim and Erhamza (2020)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Ramesh et al. (2020)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE

AUTHOR (YEAR)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	TOTAL YES	RISK
Saloni et al. (2020)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Shah et al. (2020)	Y	Y	U	Y	Y	N	Y	Y	6	MODERATE
Anerao et al. (2021)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Chandrasekhar et al. (2021)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Garg et al. (2021)	Y	Y	Y	Y	Y	U	Y	Y	7	LOW
Kumari et al. (2021)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Ojha et al. (2021)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Suguna and Ravindran (2021)	Y	Y	Y	Y	U	N	Y	Y	6	MODERATE
Arthnari et al. (2022)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Ayesha et al. (2022)	Y	Y	Y	Y	Y	N	Y	Y	7	LOW
Ingaleshwar et al. (2022)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Mohammed et al. (2022)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Shakya et al. (2022)	Y	Y	Y	Y	N	N	Y	Y	6	MODERATE
Ulusoy and Ozkara (2022)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Vora and Arthanari (2022)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Deana et al. (2023)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Esfehiani et al. (2023)	Y	Y	Y	Y	Y	Y	Y	Y	8	LOW
Qaraghoulí et al. (2023)	Y	Y	Y	Y	Y	N	Y	Y	7	LOW
Aggarwal et al. (2024)	Y	Y	U	Y	N	N	Y	Y	5	MODERATE
Arthanari et al. (2024a)	Y	Y	Y	Y	Y	N	Y	Y	7	LOW
Arthanari et al. (2024b)	Y	Y	Y	Y	Y	N	Y	Y	7	LOW
Arthanari et al. (2024c)	Y	Y	Y	Y	Y	N	Y	Y	7	LOW

Notes for Authors



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