Craniofacial Shape and Anatomical Changes Across the Human Lifespan: A Literature Review of Three Dimensional Morphometric Evidence

Gita Dwi Jiwanda Sovira[1,2], Yona Ladyventini[3]

[1]Doctoral Program in Medical Science, Faculty of Medicine, Padjadjaran University, Prof. Eyckman St., No. 38, Pasteur, Sukajadi District, Bandung City, West Java, Indonesia; [2]Department of Oral Biology, Faculty of Denstistry, Padjadjaran University, Hegarmanah, Jatinangor, Sumedang Regency, West Java, Indonesia; [3]Department of Dental Public Health, Faculty of Dentistry, Andalas University, Padang Timur, Padang City, West Sumatera, Indonesia

Background: Craniofacial morphology is a dynamic biological system that undergoes continuous changes from childhood to advanced adulthood, involving alterations in size, shape, proportions, spatial relationships, and surface configuration of the cranial vault, cranial base, midface, mandible, and facial soft tissues. Conventional two-dimensional anthropometry may inadequately capture the complex three-dimensional nature of craniofacial form. Three-dimensional imaging and morphometric techniques enable quantitative assessment of craniofacial changes across different stages of life. Objective: This literature review aims to synthesize three-dimensional morphometric evidence regarding changes in craniofacial shape, size, and anatomical relationships across the human lifespan and identify morphological patterns associated with age, sex, anatomical region, and imaging modality. Methods: A literature search was conducted in PubMed using a predefined Boolean strategy. Eligible studies included human research evaluating age-related craniofacial morphology using three-dimensional imaging or morphometric techniques, including CT and CBCT, with at least two age groups or age analyzed as a continuous variable. Data were extracted regarding population characteristics, sample size, age range, sex distribution, imaging modality, anatomical region, morphometric methods, landmarks or surface parameters, statistical analyses, and principal age-related findings. The review followed the PRISMA 2020 framework. Results: The initial PubMed search identified 71 records. After restricting the search to the last 10 years, 43 records remained. Following application of the free full-text filter, 26 articles were identified. Screening based on study population excluded non-human studies, resulting in 11 eligible studies included in the qualitative synthesis. Conclusion: Three-dimensional morphometric approaches provide a comprehensive framework for characterizing craniofacial changes across the human lifespan. Craniofacial aging involves multidimensional changes in size, shape, spatial relationships, and tissue distribution. Future research should emphasize longitudinal designs, standardized three-dimensional protocols, population-specific reference datasets, and integration of geometric morphometrics with automated computational methods.

Keywords: aging; craniofacial morphology; cranial morphology; facial morphology; lifespan; geometric morphometrics; morphometry; three-dimensional imaging

This is an open access article under theCC BY-NClicense

Corresponding Author:
Fajar Hakim
Public Health Program, Faculty of Health Sciences and Psychology, Muhammadiyah University of Pontianak
Jl. Jenderal Ahmad Yani No. 111, Pontianak, West Kalimantan
fajar7600@gmail.com

1. Introduction

Craniofacial morphology represents the integrated anatomical outcome of genetic, developmental, functional, environmental, and age-related processes.[1] From early childhood to adulthood, the craniofacial skeleton undergoes substantial changes in size and configuration, while subsequent adulthood is characterized by continuing alterations in skeletal architecture and facial soft tissue..[2] Consequently,

craniofacial morphology should be regarded not as a static anatomical characteristic but as a dynamic three-dimensional biological system that changes throughout the human lifespan.[3]

The developmental trajectory of the craniofacial complex is is complex because different anatomical regions mature and remodel at different rates.[1,4] During childhood and adolescence, the cranial vault, cranial base, maxilla, and mandible undergo region-specific growth, while structures such as the nose and mandible may continue to develop beyond the major phase of cranial growth.[1,4] After skeletal maturity, craniofacial morphology continues to change through skeletal remodeling, alterations in facial proportions, dental changes, and redistribution of soft tissues. These processes are influenced by age, sex, population characteristics, and environmental factors, resulting in heterogeneous morphological trajectories across anatomical regions.[1,5]

After skeletal maturity, craniofacial morphology continues to change.[6] Aging of the adult craniofacial complex involves alterations in bone morphology, facial proportions, soft tissue distribution, and surface configuration.[6] Earlier anthropometric and histological investigations demonstrated reductions in facial height, modest increases in facial width and depth, and increasing coarseness and porosity of bony structures with advancing age. These changes were particularly associated with the maxilla and mandible and were influenced by tooth loss and other biological factors.[6,7] The aging process is therefore not simply a consequence of generalized tissue loss.[8] Instead, craniofacial aging represents a complex interaction between skeletal remodeling, dental status, soft tissue redistribution, muscle changes, and environmental factors. A comprehensive review of adult craniofacial aging emphasized that age-related changes occur in both the bony and soft tissue components and may be influenced by sex, ancestry, lifestyle, and environmental exposure.[8,9]

The emergence of three-dimensional imaging, including computed tomography (CT), cone-beam computed tomography (CBCT), and three-dimensional facial surface imaging, has substantially improved the assessment of craniofacial morphology.[10] Unlike conventional two-dimensional anthropometry, three-dimensional approaches allow quantitative evaluation of spatial relationships, surface configuration, curvature, volume, and complex shape variation.[4]

Geometric morphometrics further extends this capability by preserving the spatial relationships among anatomical landmarks and enabling the analysis of shape independently of position, orientation, and scale through procedures such as Generalized Procrustes Analysis and subsequent multivariate analyses.[11,12]

Although the number of three-dimensional craniofacial studies has increased, the existing evidence remains fragmented and has not been comprehensively synthesized from a lifespan perspective. Previous reviews have generally addressed narrower questions, such as geometric morphometrics for craniofacial skeletal age estimation, or have focused on particular anatomical structures, populations, or applications. For example, a previous systematic review of geometric morphometrics for craniofacial skeletal age estimation identified only a small number of eligible studies and concluded that the available evidence was insufficient for quantitative meta-analysis.[13] Importantly, that review primarily addressed the potential of geometric morphometrics for estimating age rather than synthesizing the broader anatomical changes in craniofacial shape and structure that occur across different stages of life.[11,4,14]

Thus, an important gap remains in the literature is there is no sufficiently comprehensive synthesis integrating three-dimensional evidence of cranial skeletal, facial skeletal, mandibular, and facial soft-tissue changes across the human lifespan. In addition, previous evidence has varied substantially in imaging modality, anatomical region, morphometric methodology, age categorization, sex distribution, and population characteristics, making it difficult to determine which anatomical changes are consistently associated with age and how these trajectories differ according to sex and population. A lifespan-oriented

synthesis is therefore needed to move beyond age estimation as an isolated outcome and instead characterize the broader patterns of craniofacial morphological change.

The present review addresses this gap by synthesizing three-dimensional morphometric evidence of craniofacial shape, size, and anatomical relationships from adolescence through adulthood and later life. In contrast to previous reviews focused primarily on age estimation or specific craniofacial applications, this review integrates evidence from cranial skeletal, facial skeletal, mandibular, and facial soft-tissue structures and considers both conventional and geometric morphometric approaches. This framework is intended to identify anatomical regions most consistently affected by age, characterize the major morphological trajectories across the lifespan, and examine the influence of sex and population characteristics on these patterns.

Therefore, this literature review aims to synthesize available three-dimensional morphometric evidence regarding craniofacial shape and anatomical changes across the human lifespan, identify anatomical regions most consistently affected by age, compare methodological approaches, and evaluate the influence of sex, age, and population characteristics on observed morphological trajectories.

2. Methods

Study Design

This study will be conducted as a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) recommendations.

Eligibility Criteria

Eligibility criteria will be structured according to the Population, Concept, and Context framework.

Population

Human participants across any age range, including children, adolescents, adults, and older adults.

Concept

Three-dimensional assessment of craniofacial morphology, including: cranial morphology; cranial vault morphology; cranial base; cranial fossae; orbit; zygomatic complex; nasal complex; maxilla; mandible; dentoalveolar structures; facial soft tissue; whole-face morphology.

Context

Studies evaluating age-related changes, growth trajectories, developmental changes, or aging-related morphological differences.

Inclusion Criteria

Studies will be included if they investigated human craniofacial morphology, used a three-dimensional imaging or three-dimensional morphometric approach, included age as an independent variable or compared different age groups, reported quantitative or morphometric outcomes, investigated craniofacial shape, size, proportions, volume, surface configuration, or spatial relationships, were original research articles, were published in peer-reviewed journals and available in English

Exclusion Criteria

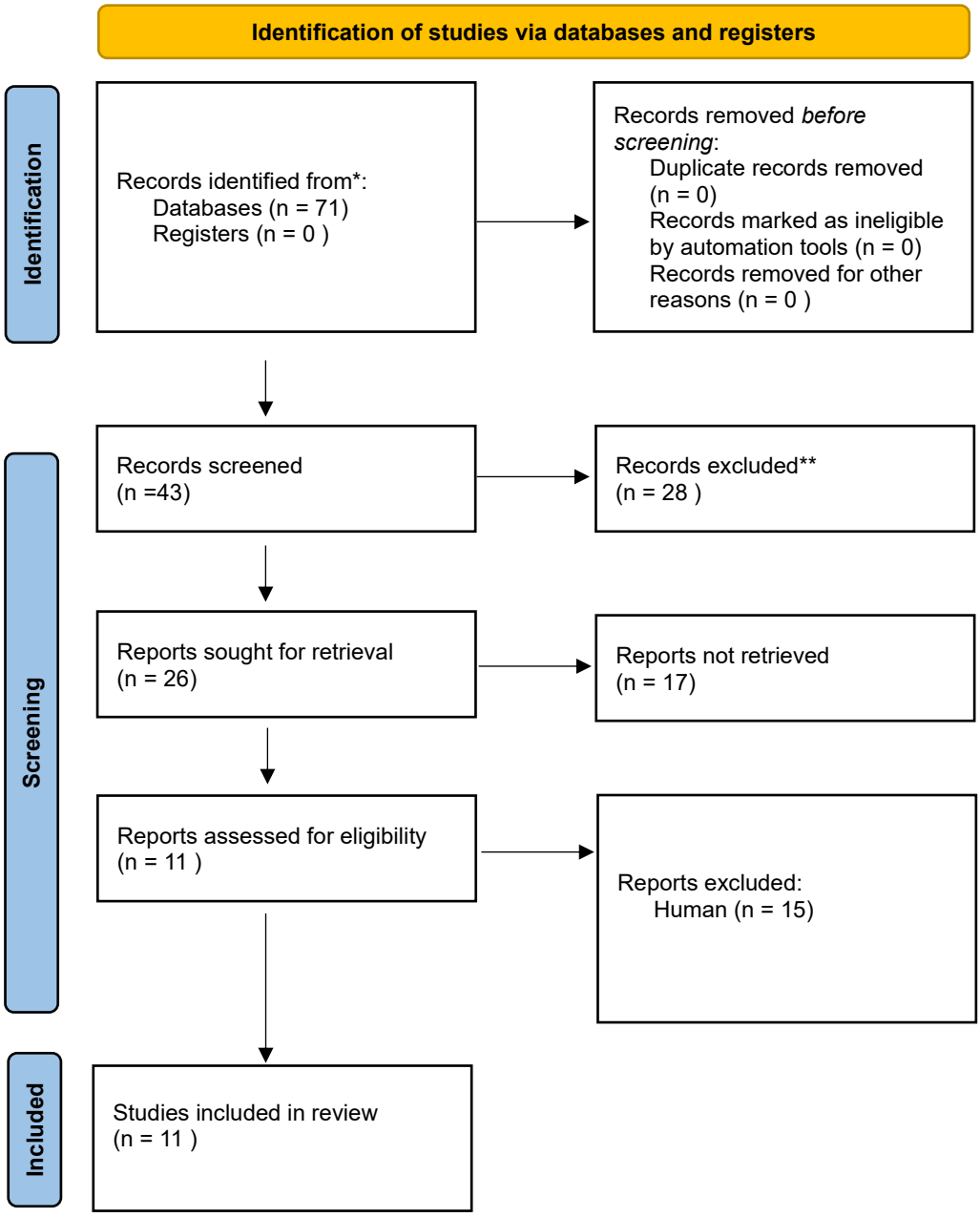
Studies will be excluded if they used exclusively two-dimensional imaging, were case reports or case series, focused exclusively on pathological craniofacial conditions unless a normal control group was available, did not provide sufficient information regarding age or morphological outcomes.

Search Strategy

The electronic literature search should be performed in PubMed databases. The following search strategy can be adapted for PubMed (("craniofacial"[Title/Abstract] OR "cranial"[Title/Abstract] OR "craniofacial morphology"[Title/Abstract] OR "facial morphology"[Title/Abstract] OR "facial shape"[Title/Abstract]) AND ("aging"[Title/Abstract] OR "ageing"[Title/Abstract] OR "age-related"[Title/Abstract] OR "growth"[Title/Abstract] OR "development"[Title/Abstract] OR "lifespan"[Title/Abstract]) AND ("three-dimensional"[Title/Abstract] OR "3D"[Title/Abstract] OR "computed tomography"[Title/Abstract] OR "cone beam computed tomography"[Title/Abstract] OR "geometric morphometric*"[Title/Abstract] OR "surface morphometric*"[Title/Abstract])).

Study Selection

All identified records will be exported into reference-management software Mendeley. Duplicate records will be removed before screening. The screening process will consist of title screening, abstract screening, full-text assessment, final inclusion. Two reviewers should independently perform screening and eligibility assessment. Disagreements should be resolved through discussion or consultation with a third reviewer. The complete selection process will be presented using a PRISMA 2020 flow diagram.



Data Extraction

The following information was extracted from each eligible study: author, publication year, journal, country, ancestry or ethnicity, sample size and sex distribution, age range, study design, imaging modality, anatomical region, morphometric approach, number and location of landmarks or semilandmarks, statistical methods, age-related findings, sex differences, principal morphological changes, clinical relevance, and methodological limitations.

Quality Assessment

The methodological quality of included studies should be evaluated using an appropriate critical appraisal tool according to study design. For observational studies, an appropriate Joanna Briggs Institute (JBI) critical appraisal checklist may be considered. Studies should not necessarily be excluded solely because of methodological limitations; instead, quality findings should be incorporated into the interpretation of the evidence.

3. Results

The initial PubMed search identified 71 records. After restricting the search to the last 10 years, 43 records remained. Following application of the free full-text filter, 26 articles were identified. Screening based on study population excluded non-human studies, resulting in 11 eligible studies included in the qualitative synthesis.

Table 1. Characteristics of the studies included in the qualitative synthesis

No.	Author	Population	Sample	Age / Age range	Sex	Imaging Modality	Morphometric approach	Key Finding
1.	Agbolade et al. (2020)	White British and White Irish European	292 scans	<13 years; 13–19; 20–29; 30–49; ≥50 years	Male and female	3dMD	Geometric morphometrics using 20 anatomical landmarks and 480 sliding semilandmarks; Procrustes-based analyses and classification	Craniofacial shape varied significantly with age, sex, and ethnicity. Sex and age explained greater morphological variation than ethnicity, with high classification accuracy for sex, age, and ethnicity.
2.	Mbonani et al. (2024)	White South Africans and French individuals	184 CBCT scans	18–80 years (South African); 18–50 years (French)	South Africa: 29 M/47 F; France: 54 M/54 F	CBCT	3D geometric morphometrics of hard- and soft-tissue facial matrices; landmark and sliding-semilandmark analyses; partial	Population affinity, sex, and age significantly influenced facial morphology. Strong covariation was observed

No.	Author	Population	Sample	Age / Age range	Sex	Imaging Modality	Morphometric approach	Key Finding
							least squares analyses	between underlying skeletal structures and selected facial soft-tissue regions, supporting population-specific approaches to craniofacial analysis.
3.	Biehler-Gomez et al. (2025)	Milanese/Italian skeletal samples from five historical periods	213 crania	Historical periods spanning approximately 2,000 years	Male and female	Dry skulls / osteological specimens	Conventional cranial morphometry; 29 standard craniofacial measurements; ANOVA, z-scores, and post-hoc comparisons	Significant secular changes were identified in eight craniofacial dimensions, including maxillo-alveolar breadth, foramen magnum dimensions, orbital breadth, biasterionic breadth, parietal chord, cranial base length, and bimaxillary breadth.
4.	Usui et al. (42026)	Historical and present-day Japanese	112 crania:	mean age approximately 55 years in present-day sample	males and females	PMCT	3D geometric morphometrics; 161 cranial landmarks; Generalized Procrustes Analysis (GPA) and Principal Component Analysis (PCA)	Cranial morphology showed secular changes over approximately one century, including brachycephalization and enlargement of the mastoid processes.

No.	Author	Population	Sample	Age / Age range	Sex	Imaging Modality	Morphometric approach	Key Finding
								Some patterns of sexual dimorphism became more pronounced in the present-day population.
5.	Mohd Fauad et al. (2026)	Malaysian adults: Malay, Chinese, and Indian populations	413 CT scans	18–65 years; groups 18–30, 31–40, 41–50, and 51–65 years	208 M/205 F	CT	3D geometric morphometrics of the maxilla using 45 anatomical landmarks; GPA, Procrustes ANOVA, PCA/CVA, and discriminant analysis	Maxillary shape differed significantly across age groups. The greatest age-related variation was localized mainly around the left maxillary region, including the zygomaxillary suture and lateral alveolar process.
6.	Urban et al. (2016)	Adults undergoing clinical CT at Wake Forest Baptist Health	122 CT scans	20–99 years	Male and female;	Clinical head CT	Dense 3D morphometry using 28,641 homologous pseudo-landmarks; GPA and age-related regression/permutation analyses	Significant age-related cranial shape changes were demonstrated. Patterns differed between sexes and among cranial regions, with significant changes particularly involving the cranial vault and anterior/middle cranial fossae.
7.	Saadé et al. (2018)	Growing patients undergoing	48 patients	Mean age 11.7 ± 1.5 years	Male and female	CBCT	3D craniofacial landmarks; Generalized Procrustes	Craniofacial centroid size was significantly

No.	Author	Population	Sample	Age / Age range	Sex	Imaging Modality	Morphometric approach	Key Finding
		orthodontic assessment					Analysis; centroid size; correlation and multiple regression analyses	associated with chronological and skeletal age. Geometric morphometrics demonstrated potential for estimating craniofacial skeletal age during growth.
8.	Cevidanes et al. (2005)	Brazilian children with Class II malocclusion or normal occlusion	78 subjects; 156 MRI scans	Approximately 9–12 years; baseline and 18 ± 1 months	Male and female	3D MRI	3D skeletal landmark-based morphometric analysis; Procrustes transformation and principal component analysis	Mandibular growth and craniofacial relationships were characterized during the pubertal growth period. Orthopedic treatment was associated with increased vertical mandibular ramus dimensions and forward displacement of the mandibular rami relative to the posterior nasomaxilla and middle cranial fossae.
9.	Lo et al. (2022)	Healthy Taiwanese/ Asian infants	66 infants; 373 3D photographs	1, 2, 4, 6, 9, and 12 months	33 M/33 F	3dMD	3D craniofacial mesh analysis; anthropometric indices; head volume and circumference; asymmetry mapping	The fastest craniofacial growth occurred between 1 and 2 months and the slowest between 9 and 12 months. Male infants

No.	Author	Population	Sample	Age / Age range	Sex	Imaging Modality	Morphometric approach	Key Finding
								generally had larger craniofacial dimensions, head volume, and circumference. Craniofacial asymmetry decreased progressively during the first year.
10.	Sardi et al. (2007)	Human fetal and early postnatal skulls	54 skulls	32–47 weeks of gestational age	Not specified as a primary comparison	3D osteological specimens / 3D landmark data	33 three-dimensional landmarks; GPA, PCA, multivariate regression of shape on centroid size, and transformation grids	Significant allometric craniofacial shape changes occurred during late prenatal and early postnatal development. Variation was greatest in the cranial vault, while the cranial base showed smaller changes and the face showed little variation during this developmental interval.
11.	Jeffery et al. (2022)	Human participants from multiple open-access MRI datasets	575 individuals	Birth–79 years; 10 chronological age bins	216 M, 189 F; 170 sex unknown	MRI	Standard craniometrics and Procrustes-based 3D morphometric analyses; 23 cranial landmarks; endocranial volume measurements and multivariate regression	Craniofacial morphology demonstrated coordinated changes across the life course. Brain-related expansion dominated early postnatal development, whereas facial

No.	Author	Population	Sample	Age / Age range	Sex	Imaging Modality	Morphometric approach	Key Finding
								expansion became particularly prominent during puberty. Cranial and facial structures behaved as partially integrated modules, with measurable age-related changes extending into adulthood and aging.

3dMD (3D stereophotogrammetry); CBCT (Cone Bean Computed tomography); PMCT (CT and post-mortem CT); CT (Computed tomography); MRI (Magnetic Resonance Imaging).

Characteristics of the Included Studies

Eleven studies were included in the qualitative synthesis, representing craniofacial morphological changes from late prenatal development to older adulthood. The studies included diverse populations from Europe, Asia, Africa, and South America. The age coverage varied considerably, from 32–47 weeks of gestation to 79 years of age. Most studies included both male and female participants, although the distribution of sex and the availability of sex-specific analyses varied among studies.

Three-dimensional imaging and morphometric approaches were predominant across the included studies. Imaging modalities included computed tomography (CT), cone-beam computed tomography (CBCT), magnetic resonance imaging (MRI), post-mortem computed tomography (PMCT), and three-dimensional stereophotogrammetry. Several studies employed geometric morphometric methods, including Generalized Procrustes Analysis (GPA), Principal Component Analysis (PCA), regression, canonical variate analysis, and discriminant analysis. Other studies used conventional cranial measurements or three-dimensional surface and mesh-based analyses. The characteristics of the included studies are summarized in Table 1.

Discussion

Across the 11 studies, craniofacial morphology demonstrated substantial variation across developmental stages, from prenatal development through infancy, adolescence, adulthood, and aging. However, the magnitude and nature of morphological change differed according to developmental stage and anatomical region.

During the prenatal and early postnatal periods, the observed changes were predominantly related to rapid growth and allometric development. Sardi et al. identified significant allometric changes in craniofacial shape between 32 and 47 weeks of gestation, with the greatest variation occurring in the cranial vault. In contrast, the cranial base and facial region demonstrated relatively smaller changes during this

developmental period. These findings indicate that craniofacial development is already characterized by regionally differentiated growth before birth.[15,16]

A similar pattern of rapid early growth was reported by Lo et al. in infants followed from 1 to 12 months. The fastest craniofacial growth occurred between 1 and 2 months, followed by progressively slower growth toward 12 months. In addition to changes in craniofacial dimensions, head volume and circumference increased, whereas craniofacial asymmetry decreased during the first year of life. Thus, early postnatal development was characterized not only by enlargement but also by progressive changes in craniofacial configuration and symmetry.[17,18]

During childhood and adolescence, craniofacial changes remained strongly associated with growth and maturation. Saadé et al. demonstrated significant associations between craniofacial centroid size and both chronological and skeletal age, supporting the relationship between three-dimensional craniofacial morphology and biological maturation. Similarly, Cevidanes et al. demonstrated measurable mandibular and craniofacial changes during an approximately 18-month period in children aged approximately 9–12 years. These findings indicate that the mandible and other craniofacial structures undergo substantial morphological remodeling during the growth period.[19,20]

The broadest life-course evidence was provided by Jeffery et al., who examined individuals from birth to 79 years across ten chronological age groups. Their findings demonstrated coordinated but non-uniform craniofacial changes throughout life. Brain-related expansion was particularly prominent during early postnatal development, whereas facial expansion became more prominent during puberty. Cranial and facial structures also demonstrated partially integrated patterns of morphological change, suggesting that craniofacial development involves both coordinated and region-specific processes.[21]

After skeletal maturation, measurable craniofacial changes continued into adulthood and later life. Urban et al. identified significant age-related changes in adult cranial morphology across individuals aged 20–99 years. The observed changes were not uniform across the skull, with different cranial regions demonstrating different patterns of age-related variation. Similarly, Mohd Fauad et al. demonstrated significant differences in maxillary shape among Malaysian adults aged 18–65 years, indicating that age-associated morphological variation remains detectable after the major period of craniofacial growth.[22]

Three-dimensional analysis of the adult skull indicates that aging is associated with changes in the morphology of the cranial vault and cranial fossae.[23] Urban et al. evaluated CT-derived skull morphology in individuals aged 20–100 years using thousands of three-dimensional landmarks. After registration and generalized Procrustes analysis, significant age-related shape changes were identified in several cranial regions. In males, changes were observed in most analyzed regions except the posterior cranial fossa, whereas females demonstrated significant changes particularly in the middle and anterior cranial fossae. These findings suggest that cranial aging is not spatially homogeneous. Instead, specific anatomical regions may undergo differential remodeling, potentially reflecting interactions between skeletal remodeling, brain morphology, mechanical loading, and biological aging.[13]

Earlier anthropometric research similarly demonstrated that aging is associated with increased cranial porosity and changes in facial skeletal dimensions. However, three-dimensional morphometric approaches provide additional information by characterizing changes in spatial configuration rather than relying exclusively on individual linear measurements.[24]

Facial Skeletal Changes

The facial skeleton demonstrates region-specific changes with advancing age.[16,25] Three-dimensional geometric morphometric analyses have identified age-related alterations in the orbital region, zygomatic complex, nasal aperture, and maxillary alveolar process. These changes may involve modifications in

curvature, projection, and spatial relationships between anatomical regions.[12] Such findings are important because conventional anthropometric measurements may detect a change in distance between two landmarks but may not adequately represent how the surrounding surface changes.[26] For example, an apparently stable linear distance may coexist with a substantial change in local curvature or three-dimensional orientation.[27,28] This limitation supports the use of shape-based methods for investigating age-related craniofacial remodeling.

Mandibular Changes

The mandible is particularly important in lifespan craniofacial analysis because it continues to undergo remodeling throughout adulthood. Age-related mandibular changes may involve reduction in alveolar height, alteration of mandibular body morphology, changes in ramus configuration, modification of mandibular angle, changes in chin projection, changes associated with tooth loss, alterations in cortical morphology.[29,30] The magnitude of these changes is highly variable because mandibular morphology is influenced not only by chronological age but also by dentition, occlusion, masticatory loading, sex, and systemic skeletal changes.[31] Consequently, mandibular morphology should preferably be evaluated using multiple complementary measurements rather than a single linear parameter.

Three-Dimensional Facial Soft Tissue Changes

Three-dimensional facial surface analysis has produced some of the most detailed evidence concerning lifespan changes.[32] Velemínská et al. analyzed 456 three-dimensional facial models from individuals aged 14–83 years and demonstrated that facial aging can be modeled as a continuous trajectory rather than a simple comparison between young and old groups. Importantly, the study also demonstrated sex-specific differences in the magnitude and trajectory of facial changes.[33] A much larger 2026 study involving 4,038 individuals aged 5–85 years further demonstrated continuous facial morphological change across the lifespan. The authors identified age-related alterations in the forehead, temples, periorbital region, cheeks, nasolabial region, and lips. The most pronounced changes occurred during middle and later adulthood, while the overall trajectory differed between males and females. These findings reinforce the concept that facial aging is multidimensional. Changes do not occur uniformly across the face but involve coordinated modifications in vertical, sagittal, and transverse dimensions.[34,35]

Geometric Morphometrics as a Tool for Lifespan Analysis

One of the major developments in craniofacial research has been the application of geometric morphometrics.[11] Traditional morphometrics generally relies on individual distances, angles, ratios, or areas. While these measurements are clinically useful, they reduce complex three-dimensional anatomical structures to a limited number of variables.[36] Geometric morphometrics preserves the spatial relationships among anatomical landmarks. Following landmark acquisition, generalized Procrustes analysis can be used to remove variation attributable to translation, rotation, and scale, allowing subsequent analysis to focus on shape.[12,37,38] Principal Component Analysis can then be used to identify dominant patterns of shape variation, while regression can assess the relationship between shape and chronological age.[39] This approach is particularly relevant for lifespan research because aging is not necessarily associated with a simple increase or decrease in one measurement. Instead, aging may involve coordinated changes across multiple anatomical landmarks. A previous systematic review of geometric morphometrics for craniofacial skeletal age estimation concluded that the method has potential for age estimation, but also emphasized the limited number of available studies and insufficient methodological consistency for quantitative meta-analysis.[40]

The present review therefore expands the scope beyond age estimation and considers the broader anatomical question of how craniofacial shape itself changes across the lifespan.

Influence of Sex on Craniofacial Aging

Sex is an important source of biological variation in craniofacial morphology.[41] The trajectory of craniofacial aging is not identical in males and females. Differences may arise from variations in skeletal development, hormonal changes, bone remodeling, soft tissue distribution, and patterns of facial adiposity.[41] Three-dimensional skull analysis has demonstrated sex-specific age-related patterns in cranial morphology. Urban et al. found that the regions exhibiting significant age-related shape changes differed between males and females.[13] Similarly, three-dimensional facial analysis has demonstrated that males and females may share a broadly similar aging trajectory while differing in the magnitude and rate of individual morphological changes. Therefore, future three-dimensional craniofacial reference models should ideally be sex-specific or incorporate sex as an important covariate.

Influence of Population and Ancestry

Population variation represents another major consideration.[42] Craniofacial morphology is influenced by genetic ancestry, environmental conditions, nutrition, socioeconomic factors, and secular trends. Consequently, age-related patterns identified in one population cannot automatically be generalized to another.[42,43] This issue is particularly important for Southeast Asian populations, which remain comparatively underrepresented in large three-dimensional craniofacial datasets. Most large-scale three-dimensional facial aging studies have focused on European or East Asian populations.[43] Therefore, population-specific studies are necessary to establish appropriate normative trajectories for Indonesian populations. This represents an important research gap and provides a strong rationale for future studies using Indonesian CT and three-dimensional facial datasets.

The evidence synthesized in this review supports the concept that craniofacial morphology is continuously dynamic throughout the human lifespan. Rather than following a simple linear trajectory, craniofacial changes appear to involve several overlapping processes. During childhood and adolescence, growth dominates morphological variation. During adulthood, remodeling and tissue redistribution become increasingly important. In older adulthood, skeletal remodeling, bone resorption, dental changes, and soft tissue alterations may produce additional changes in craniofacial configuration.[34,44,45]

One of the most important findings emerging from three-dimensional studies is the regional heterogeneity of craniofacial aging. The cranial vault, cranial fossae, orbit, zygomatic region, nasal complex, maxilla, mandible, and facial soft tissues do not necessarily change at the same rate. This finding challenges the traditional concept of craniofacial aging as a generalized reduction in facial dimensions.[9] Three-dimensional geometric morphometrics provides an important methodological advantage because it enables researchers to quantify changes in configuration rather than isolated measurements. The use of GPA, PCA, regression, and deformation visualization allows age-associated trajectories to be represented more comprehensively.[11]

However, the literature also demonstrates considerable methodological heterogeneity. Different studies use different age categories, imaging systems, landmark definitions, anatomical regions, and statistical methods.[2,25,46] Some studies focus on linear measurements, while others use dense surface correspondence or landmark-based geometric morphometrics.[47]

This heterogeneity limits direct comparison between studies and is one of the major barriers to quantitative meta-analysis. Another important issue is the predominance of cross-sectional research. Most available studies compare individuals from different age groups rather than following the same individuals longitudinally. Cross-sectional studies are useful for identifying population-level age trends but cannot completely distinguish biological aging from cohort effects. Longitudinal three-dimensional datasets would therefore provide stronger evidence for individual craniofacial aging trajectories.

Population representation is another important limitation. Large three-dimensional datasets have predominantly originated from European and selected Asian populations. The recent large European-ancestry study involving more than 4,000 individuals demonstrates the value of large datasets for modeling age-related facial trajectories, but its findings cannot automatically be generalized to other populations. For Indonesia, this limitation is particularly relevant because the country contains substantial population diversity and craniofacial morphology may differ from populations in Europe, East Asia, or other geographic regions. Therefore, development of Indonesian three-dimensional craniofacial reference datasets should become an important research priority.

Strengths and Limitations of the Review

This review integrates three-dimensional evidence of both skeletal and soft tissue morphology across the human lifespan, incorporating conventional and geometric morphometric approaches to provide a comprehensive perspective on craniofacial development and aging. However, heterogeneity in populations, imaging modalities, age groups, and morphometric methods, along with the predominance of cross-sectional studies and differences in ancestry and sex distribution, may limit comparability, generalizability, and quantitative synthesis.

4. Conclusion

Three-dimensional morphometric evidence demonstrates that craniofacial morphology undergoes continuous and region-specific changes throughout the human lifespan. These changes involve not only alterations in linear dimensions but also complex modifications in three-dimensional shape, curvature, spatial relationships, and tissue distribution. During childhood and adolescence, craniofacial variation is primarily characterized by growth and developmental remodeling. In adulthood, continuing skeletal remodeling and changes in facial soft tissues produce progressive alterations in facial configuration. During later life, these processes become increasingly influenced by skeletal resorption, dental changes, soft tissue redistribution, and sex-specific biological factors. Geometric morphometrics provides an important methodological framework for capturing these complex changes because it preserves spatial relationships among anatomical landmarks and enables the analysis of shape trajectories. However, current evidence remains heterogeneous, with substantial differences in population characteristics, imaging techniques, landmark protocols, and statistical approaches. Large longitudinal datasets and standardized three-dimensional protocols are therefore needed.

5. References

1. Rajasekaran A, Gupta S, Al-Hassiny A, Rana SS, Chaudhari PK. An Overview of 3D Craniofacial Imaging. In: Applications of Three-dimensional Imaging for Craniofacial Region. Singapore: Springer Nature Singapore; 2024. p. 1–7. doi:10.1007/978-981-97-4608-8_1
2. Maken P, Rana SS, Gupta A, Kaur H. Challenges for 3D Imaging for Craniofacial Applications. In: Applications of Three-dimensional Imaging for Craniofacial Region. Singapore: Springer Nature Singapore; 2024. p. 223–40. doi:10.1007/978-981-97-4608-8_15
3. Knigge RP, Hardin AM, Middleton KM, McNulty KP, Oh HS, Valiathan M, et al. Craniofacial growth and morphology among intersecting clinical categories. Anatomical Record. 2022 Sep 1;305(9):2175–206. doi:10.1002/ar.24870 PubMed PMID: 35076186.
4. Katyal S, Vichare S, Rana SS, Maken P, Gupta A. Three-Dimensional Superimposition of Craniofacial Structures. In: Applications of Three-dimensional Imaging for Craniofacial Region. Singapore: Springer Nature Singapore; 2024. p. 183–99. doi:10.1007/978-981-97-4608-8_13

5. Hu Z, Zhang Y, Liu N, Gao X, Huang Z, Wu G, et al. Quantification of Craniofacial Growth Pattern Based on Deep Learning. Bioengineering. 2026 Feb 27;13(3):277. doi:10.3390/bioengineering13030277
6. Wilkinson C, Liu CYJ, Shrimpton S, Greenway E. Craniofacial identification standards: A review of reliability, reproducibility, and implementation. Forensic Sci Int. 2024 Jun;359:111993. doi:10.1016/j.forsciint.2024.111993
7. Smith OAM, Nashed YSG, Duncan C, Pears N, Profico A, O'Higgins P. 3D Modeling of craniofacial ontogeny and sexual dimorphism in children. Anat Rec (Hoboken). 2021 Sep;304(9):1918–26. doi:10.1002/ar.24582 PubMed PMID: 33336527.
8. Velemínská J, Jaklová LK, Kočandrlová K, Hoffmannová E, Koudelová J, Suchá B, et al. Three-dimensional analysis of modeled facial aging and sexual dimorphism from juvenile to elderly age. Sci Rep. 2022 Dec 17;12(1):21821. doi:10.1038/s41598-022-26376-8 PubMed PMID: 36528705.
9. Jeffery NS, Humphreys C, Manson A. A human craniofacial life-course: Cross-sectional morphological covariations during postnatal growth, adolescence, and aging. Anat Rec (Hoboken). 2022 Jan;305(1):81–99. doi:10.1002/ar.24736 PubMed PMID: 34369671.
10. Small C, Schepartz L, Hemingway J, Brits D. Three-dimensionally derived interlandmark distances for sex estimation in intact and fragmentary crania. Forensic Sci Int. 2018;287:127–35. doi:10.1016/j.forsciint.2018.02.012
11. Desai P, Awatiger MM, Angadi P. Geometrics Morphometrics in Craniofacial Skeletal Age Estimation - A Systematic Review. J Forensic Odontostomatol. 2023;41(1):57–64.
12. Knigge RP, McNulty KP, Oh H, Hardin AM, Leary E V., Duren DL, et al. Geometric morphometric analysis of growth patterns among facial types. American Journal of Orthodontics and Dentofacial Orthopedics. 2021 Sep 1;160(3):430–41. doi:10.1016/j.ajodo.2020.04.038 PubMed PMID: 34175161.
13. Urban JE, Weaver AA, Lillie EM, Maldjian JA, Whitlow CT, Stitzel JD. Evaluation of morphological changes in the adult skull with age and sex. J Anat. 2016 Dec 18;229(6):838–46. doi:10.1111/joa.12247
14. Kostares M, Pantazis N, Papanagiotou P, Kostares E, Benetou V, Samolis A, et al. Sex Estimation Using Reproducible Craniometric Traits in a Modern Greek Population: A Pilot Craniofacial Study. Journal of Craniofacial Surgery. 2026 Apr 3. doi:10.1097/SCS.0000000000012735
15. Sardi ML, Ventrice F, Ramírez Rozzi F. Allometries Throughout the Late Prenatal and Early Postnatal Human Craniofacial Ontogeny. Anat Rec. 2007 Sep 23;290(9):1112–20. doi:10.1002/ar.20581
16. Doumit CM, Saade A, Will LA. Changes in the Shape of Craniofacial Skeleton in Children Prenatally Exposed To Anticonvulsant Drugs: a Geometric Morphometric Study. Res Sq. 2023 Dec 20;(1):1–20. doi:10.21203/rs.3.rs-3749790/v1
17. Lo Giudice A, Ronsivalle V, Gastaldi G, Leonardi R. Assessment of the accuracy of imaging software for 3D rendering of the upper airway, usable in orthodontic and craniofacial clinical settings. Prog Orthod. 2022 Dec 1;23(1). doi:10.1186/s40510-022-00413-8 PubMed PMID: 35691961.
18. Lo AL, Hallac RR, Chen SH, Hsu KH, Wang SW, Chen CH, et al. Craniofacial Growth and Asymmetry in Newborns: A Longitudinal 3D Assessment. Int J Environ Res Public Health. 2022 Oct 1;19(19). doi:10.3390/ijerph191912133
19. Saadé A, Baron P, Noujeim ZE, Arouk E, Azar D. Predictability of Craniofacial Skeletal Age with Geometric Morphometrics. J Contemp Dent Pract. 2018 Dec;19(12):1494–501. doi:10.5005/jp-journals-10024-2455
20. Cevidanes LHS, Franco AA, Gerig G, Proffit WR, Slice DE, Enlow DH, et al. Assessment of mandibular growth and response to orthopedic treatment with 3-dimensional magnetic resonance images.

American Journal of Orthodontics and Dentofacial Orthopedics. 2005 Jul;128(1):16–26. doi:10.1016/j.ajodo.2004.03.032

21. Jeffery NS, Humphreys C, Manson A. A human craniofacial life-course: Cross-sectional morphological covariations during postnatal growth, adolescence, and aging. Anat Rec. 2022 Jan 23;305(1):81–99. doi:10.1002/ar.24736
22. Mohd Fauad MF, Alias A, Choy KW, Mohd Hadi H, Chung E, Ng WL, et al. Age related morphological variation of the maxilla: a 3-dimensional (3D) geometric morphometrics analysis. Egypt J Forensic Sci. 2026 Aug 25;16(1):78. doi:10.1186/s41935-026-00574-1
23. Haslan H, Zulkiflee NDI, Alias A, Hadi H, Ker Woon C. Sexual dimorphism of cranial fossae in forensic anthropology: A systematic review. J Taibah Univ Med Sci. 2026 Jun;21(3):393–410. doi:10.1016/j.jtumed.2026.03.014
24. Uppada UK, Tauro DP, Senthilnathan KP. Anthropometric Analysis of Indian Faces: A Systematic Review. J Maxillofac Oral Surg. 2024 Jun;23(3):451–61. doi:10.1007/s12663-024-02185-6 PubMed PMID: 38911415.
25. Garvin HM, Sholts SB, Mosca LA. Sexual dimorphism in human cranial trait scores: Effects of population, age, and body size. Am J Phys Anthropol. 2014 Jun 4;154(2):259–69. doi:10.1002/ajpa.22502
26. Hallgrimsson B, Percival CJ, Green R, Young NM, Mio W, Marcucio R. Morphometrics, 3D Imaging, and Craniofacial Development. In: Current Topics in Developmental Biology. Academic Press Inc.; 2015. p. 561–97. doi:10.1016/bs.ctdb.2015.09.003 PubMed PMID: 26589938.
27. Pink CM, Maier C, Pilloud MA, Hefner JT. Cranial Nonmetric and Morphoscopic Data Sets. In: Biological Distance Analysis. Elsevier; 2016. p. 91–107. doi:10.1016/B978-0-12-801966-5.00005-6
28. Paoloni V, Gastaldi G, Franchi L, De Razza FC, Cozza P. Evaluation of the morphometric covariation between palatal and craniofacial skeletal morphology in class III malocclusion growing subjects. BMC Oral Health. 2020 May 27;20(1). doi:10.1186/s12903-020-01140-4 PubMed PMID: 32460800.
29. Zulkifli NAF, Mohd Saaid NAS, Alias A, Mohamed Ibrahim N, Woon CK, Kurniawan A, et al. Age estimation from mandibles in Malay: A 2D geometric morphometric analysis. J Taibah Univ Med Sci. 2023 Dec 1;18(6):1435–45. doi:10.1016/j.jtumed.2023.05.020
30. Alias A, Rosli SAA, Rezadin A, Mohamed Ibrahim N, Kurniawan A, Prasthanika PMM, et al. FORENSIC AGE ESTIMATION IN CHILDREN USING CORONOID PROCESS OF MANDIBLE FROM DENTAL PANORAMIC TOMOGRAPHY: A GEOMETRIC MORPHOMETRIC STUDY. LexForensica: Journal of Forensic Justice and Socio-Legal Research. 2025 Dec 1;2(2):13–22. doi:10.33102/sm6khk04
31. Cappella A, Gibelli D, Vitale A, Zago M, Dolci C, Sforza C, et al. Preliminary study on sexual dimorphism of metric traits of cranium and mandible in a modern Italian skeletal population and review of population literature. Leg Med. 2020 May;44:101695. doi:10.1016/j.legalmed.2020.101695
32. Solazzo R, Cappella A, Gibelli D, Dolci C, Tartaglia G, Sforza C. Three-Dimensional Geometric Morphometric Characterization of Facial Sexual Dimorphism in Juveniles. Diagnostics. 2025 Feb 1;15(3). doi:10.3390/diagnostics15030395
33. Roessler HI, Shields K, Grange DK, Knoers NVAM, van Haaften G, Hammond P, et al. Three-dimensional facial morphology in Cantú syndrome. Am J Med Genet A. 2020 May 1;182(5):1041–52. doi:10.1002/ajmg.a.61517 PubMed PMID: 32100467.

34. Silinevica S, Nassereldine A, Jakobsone G, Xiong J. Transverse Growth of Facial Soft Tissues: A Longitudinal Three-Dimensional Facial Growth Study. Orthod Craniofac Res. 2026 Mar 3. doi:10.1111/ocr.70109
35. Salinas CA, Liu A, Sharaf BA. Facial Morphometrics in Black Celebrities: Contemporary Facial Analysis Using an Artificial Intelligence Platform. J Clin Med. 2023 Jul 1;12(13). doi:10.3390/jcm12134499
36. Neha. Sizing the shape: Understanding morphometrics. Journal of Clinical and Diagnostic Research. 2015 Jan 1;9(1):21–6. doi:10.7860/JCDR/2015/8971.5458
37. Freudenthaler J, Čelar A, Ritt C, Mitteröcker P. Geometric morphometrics of different malocclusions in lateral skull radiographs. Journal of Orofacial Orthopedics. 2017 Jan 1;78(1):11–20. doi:10.1007/s00056-016-0057-x PubMed PMID: 27796401.
38. Sazgar T, Al-Jaf N, Norman N, Alias A. A geometric morphometric evaluation of facial hard tissue patterns. J Orthod Sci. 2022 Jan 1;11(1):24. doi:10.4103/jos.jos_199_21
39. Bookstein FL. Reworking Geometric Morphometrics into a Methodology of Transformation Grids. Evolutionary Biology. Springer; 2023. p. 275–99. doi:10.1007/s11692-023-09607-2
40. Freudenthaler J, Čelar A, Ritt C, Mitteröcker P. Geometric morphometrics of different malocclusions in lateral skull radiographs. Journal of Orofacial Orthopedics / Fortschritte der Kieferorthopädie. 2017 Jan 31;78(1):11–20. doi:10.1007/s00056-016-0057-x
41. Tallman SD. Cranial Nonmetric Sexual Dimorphism and Sex Estimation in East and Southeast Asian Individuals. Forensic Anthropology. 2019 Dec 5;2(4):204–21. doi:10.5744/fa.2019.1010
42. Ker Woon C, Basil Peter A, Ismaliza Binti Ismail N, Mikhail Syahmi Bin Azmi M, Alia Binti Irwan Benjamina Q, Dayini Binti Dasuki N, et al. Population-specific sexual dimorphism in phalanges: development of forensic models using radiographs in the contemporary Malaysian population. Australian Journal of Forensic Sciences. 2026. doi:10.1080/00450618.2026.2617321
43. Wen YF, Wong HM, McGrath CP. Developmental shape changes in facial morphology: Geometric morphometric analyses based on a prospective, population-based, Chinese cohort in Hong Kong. PLoS One. 2018 Nov 1;14(6). doi:10.1371/journal.pone.0218542 PubMed PMID: 31252428.
44. Richmond S, Howe LJ, Lewis S, Stergiakouli E, Zhurov A. Facial genetics: A brief overview. Frontiers in Genetics. Frontiers Media S.A.; 2018. doi:10.3389/fgene.2018.00462
45. Gkantidis N, Stucki S, Ghamri M, Halazonetis D, Kanavakis G. Influence of facial shape on perceived attractiveness. Prog Orthod. 2026 Mar 25;27(1):13. doi:10.1186/s40510-026-00617-2
46. Harnádková K, Kočandrlová K, Kožejová Jaklová L, Dupej J, Velemínská J. The effect of sex and age on facial shape directional asymmetry in adults: A 3D landmarks-based method study. PLoS One. 2023;18(8):e0288702. doi:10.1371/journal.pone.0288702 PubMed PMID: 37535545.
47. Swift L, Obertova Z, Flavel A, Murray K, Franklin D. Estimation of sex from cranial measurements in an Australian population. Australian Journal of Forensic Sciences. 2023;55(6):755–70. doi:10.1080/00450618.2022.2081358