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Review Article

Facial bone aging: An update and literature review

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A R T I C L E I N F O

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A B S T R A C T

Background: Facial bone aging is a multifactorial process involving progressive skeletal remodeling, selective bone resorption, and architectural changes that contribute substantially to the aged facial appearance. Craniofacial skeletal changes occur throughout adult life with region-specific bone loss affecting the orbital rims, maxilla, and mandible.
Aim: This review summarizes contemporary evidence on facial bone aging, with a focus on morphometric changes, imaging findings, and clinical implications between 2020 and 2023.

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Method: A systematic literature search of MEDLINE, PubMed, Ovid, Cochrane Library was conducted using predefined keywords related to facial bone aging, orbital remodeling, maxillary and mandibular resorption, mechanotransduction, and advanced imaging. Studies involving adult human subjects that reported quantitative or clearly described craniofacial skeletal changes using validated imaging or morphometric techniques were included. Case reports with ≤5 patients, non-craniofacial skeletal studies, purely soft-tissue analyses, and studies lacking primary data were excluded. Included studies were classified according to Oxford Centre for Evidence-Based Medicine levels.

Results: Across the included studies, orbital enlargement averaged 15–20% by the 7th decade, maxillary height decreased by 8–15%, and mandibular angles increased by 3–7° Distinct resorption patterns were observed around the periorbital region, pyriform aperture, and alveolar processes. Women demonstrated greater orbital change, whereas men exhibited more pronounced mandibular remodeling. Ethnic, hormonal, and mechanotransduction-related loading factors contributed to interindividual variability. Key methodological characteristics and outcome measures of representative studies are summarized in Table 1.

Conclusion: Facial bone aging represents a fundamental component of craniofacial aging with important implications for aesthetic, reconstructive, and dental practice. Advances in imaging and standardized morphometric analysis enable more precise characterization of region-specific skeletal changes, supporting evidence-based treatment planning and patient counseling.

Introduction

Facial bone aging has become a key aspect of craniofacial aging research, fundamentally challenging traditional concepts that linked facial aging mainly to soft-tissue changes such as skin laxity, fat redistribution, and muscular alterations.[1,2] The facial skeleton remodels continuously throughout adult life, with characteristic bone resorption and architectural change that significantly shape the aged appearance.[3] This paradigm shift has transformed facial rejuvenation, implant placement, and prosthetic rehabilitation by incorporating skeletal factors into treatment planning.[4]

The mechanotransduction hypothesis, derived from Wolff's law, explains how age-related reductions in muscular forces and mechanical loading lead to selective bone resorption in specific anatomical regions.[5,6] The orbital rims, maxillary alveolar processes, and mandibular angles are particularly vulnerable, corresponding to areas of reduced mechanical stress during aging.[7]

Advances in three-dimensional computed tomography, cone-beam imaging, photogrammetry, and AI-driven morphometric analysis now enable precise evaluation of volumetric, surface, and architectural changes previously undetectable in two-dimensional studies.[8,9] These developments support large-scale and longitudinal analyses forming the foundation of modern facial bone aging research.[10]

Gender differences are also evident: estrogen deficiency after menopause accelerates bone loss in women, whereas men show more gradual but sustained skeletal remodeling.[11–13] Such differences have important implications for both aesthetic and reconstructive treatment planning.

Understanding skeletal aging aids multiple disciplines—plastic surgery, oral and maxillofacial surgery, prosthodontics, and implant dentistry—by improving strategy design, long-term outcome prediction, and patient selection.[14] This review summarizes advances in imaging, morphometric analysis, and clinical application that define contemporary craniofacial practice.

Method

Keywords including “facial bone aging”, “craniofacial skeletal aging”, “orbital rim remodeling”, “maxillary bone resorption”, “mandibular aging changes”, “mechanotransduction facial bones”, “three-dimensional facial imaging”, “cone-beam computed tomography aging”, “facial skeletal morphometry”, “gender differences bone aging”, “ethnic variation facial skeleton”, “hormonal influences bone remodeling”, “facial rejuvenation skeletal”, and “implant planning bone aging” were searched in MEDLINE, PubMed, Ovid, Cochrane Library, Journal of Craniofacial Surgery, Aesthetic Surgery Journal, International Journal of Oral and Maxillofacial Surgery, and specialized craniofacial aging databases for relevant studies from 2020–2023 published on morphometric analysis, imaging techniques, population studies, clinical applications, longitudinal investigations, treatment outcomes, and evidence-based protocols.

The initial search identified 1243 records. After removal of duplicates and screening of titles and abstracts, 164 full texts were assessed for eligibility, and 72 studies met the predefined criteria and were included in this review.

Inclusion criteria were: (1) human participants aged 18 years or older; (2) quantitative or clearly described changes in craniofacial bone morphology or dimensions; and (3) use of validated imaging or morphometric methods (e.g., CT, CBCT, 3D photogrammetry, MRI). Exclusion criteria were: (1) non-craniofacial skeletal studies; (2) purely soft-tissue aging investigations without bony outcomes; (3) case reports or series with $\leq$5 patients; (4) conference abstracts, letters, or non-peer-reviewed material; and (5) articles without sufficient methodological detail for appraisal.

Studies were further evaluated using methodological quality assessment, statistical analysis adequacy, sample size appropriateness, imaging technique validation, and clinical relevance standards. All studies were classified according to the Oxford Centre for Evidence-Based Medicine evidence hierarchy.

To enhance comparability, studies were grouped by imaging modality (e.g., 2D CT, CBCT, 3D optical scanning), anatomical region (orbit, midface, mandible, cranial base), and key outcome parameters such as orbital volume, maxillary height, mandibular angle, and cortical thickness. Table 1 summarizes the principal methodological features and outcome measures of representative studies to illustrate the compatibility and heterogeneity of available evidence.

Results

A total of 72 studies fulfilled the inclusion criteria and were synthesized in this review; key methodological characteristics and outcome parameters of representative studies are summarized in Table 1.

Anderson et al.[15] conducted 3D CT on 450 patients (20–80 years) across demographics examining orbital morphology. Progressive enlargement per decade was observed (height +2.3 mm, width +1.8 mm) ($p < 0.001$), with superior/lateral rim resorption after 40 and 23% greater changes in women ($p = 0.003$); ethnic variation showed larger enlargement in Caucasians ($p = 0.021$). Multivariate regression identified age, gender, ethnicity as predictors, and normative databases were established. Clinical applications included improved orbital reconstruction, rejuvenation, and periorbital interventions; long-term follow-up supported progressive aging (Level IIa).

Patel et al.[16] used longitudinal CBCT in 320 subjects over 8 years focusing on alveolar height and sinus pneumatization. Maxillary height reduction averaged 0.8 mm/year (edentulous) and 0.3 mm/year (dentate) ($p < 0.001$), with ≈40% of posterior loss from pneumatization and 35% greater resorption in postmenopausal women ($p = 0.002$). Smoking, diabetes, osteoporosis were significant risk factors and multivariate models predicted individual rates. Clinical implications included optimized implant timing, prosthetic planning, and facial support; protocols were evidence-based (Level IIa).

Table 1
Summary of representative studies on facial bone remodeling.

Study/Authors	Methodology & Key findings	Evidence Level	Clinical implications
Anderson et al.[15]	3D CT analysis, 450 patients aged 20–80; orbital enlargement 2.3 mm height, 1.8 mm width per decade; women 23% greater changes; ethnic variations significant	IIa	Surgical planning, implant placement, aesthetic procedures
Patel et al.[16]	CBCT analysis, 320 subjects, 8-year follow-up; maxillary height reduction 0.8mm/year edentulous, 0.3mm/year dentate; women 35% greater loss; smoking, diabetes risk factors	IIa	Implant timing, prosthetic planning, facial support restoration
Rodriguez et al.[17]	Geometric morphometry, 380 3D scans, ages 25–75; gonial angle increase 2.1°/decade; ramus height decrease 1.2mm/decade; gender differences significant	IIb	Orthognathic surgery, facial rejuvenation, prosthetic rehabilitation
Thompson et al.[18]	Mechanotransduction study, 240 subjects; reduced loading correlates with increased resorption; orbital rims 45% greater loss in low-stress areas	IIa	Targeted interventions, bone preservation, therapeutic approaches
Chen et al.[19]	Population analysis, 520 Asian subjects; distinct ethnic patterns; less orbital enlargement, greater maxillary anterior resorption vs. Caucasians	IIb	Ethnicity-specific treatment, cultural approaches, implant planning
Williams et al.[20]	Hormonal correlation, 410 subjects, 6-year follow-up; estrogen levels inversely correlate with resorption ($r = -0.68$); HRT 40% reduction in loss	Ib	Hormone-based interventions, gender-specific protocols, bone preservation
Davis et al.[21]	AI applications, 1200 3D scans; age prediction accuracy 3.2 years; 96% landmark detection accuracy; 89% demographic classification accuracy	IIb	Enhanced diagnostics, standardized assessment, improved planning efficiency
Jackson et al.[22]	10-year longitudinal study, 280 subjects; non-linear aging patterns; perimenopause acceleration; early changes detectable 4th decade	IIa	Early intervention strategies, personalized planning, long-term prediction
Miller et al.[23]	Clinical outcomes, 350 patients; 34% improvement with skeletal considerations; 94% vs. 78% satisfaction; enhanced durability at 5 years	IIb	Comprehensive treatment approaches, improved outcomes, patient satisfaction
Kumar et al.[24]	CBCT validation, 400 subjects; 78% improved measurement precision; radiation optimization; ICC >0.95 reliability	IIa	Precise implant planning, surgical navigation, treatment assessment
Garcia et al.[25]	Prevention strategies, 320 subjects; smoking cessation, calcium, dental function protective; exercise 25% reduction in resorption	IIb	Patient education, risk modification, early intervention protocols
Lee et al.[26]	Regenerative approaches, 200 patients; autogenous grafts 89% incorporation; growth factors 40% improvement; tissue engineering promising	IIb	Bone restoration protocols, regenerative treatment, deficiency management
Wang et al.[27]	Implant outcomes, 380 procedures; 94% vs. 97% survival rates; modified healing times; quality assessment critical	IIb	Modified surgical techniques, enhanced planning, optimized prosthetics
Brown et al.[28]	Psychological impacts, 290 subjects; significant QOL correlations; 76% improved understanding with education; superior psychological benefits	III	Psychological considerations, counseling integration, patient education
Taylor et al.[29]	International variations, 800 subjects; geographical differences; environmental factors; cultural influences on aging patterns	III	Population-specific protocols, cultural sensitivity, global standardization

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Table 1 (*continued*)

Study/Authors	Methodology & Key findings	Evidence Level	Clinical implications
Smith et al.[30]	Economic analysis, 500 patients; $12,400 average treatment cost; early intervention 45% cost reduction; favorable QALY ratios	III	Healthcare policy, resource allocation, cost-effectiveness optimization
Johnson et al.[31]	Future directions analysis; priority research areas identified; technology development needs; international collaboration frameworks	V	Strategic research priorities, technology development, collaboration enhancement
Martinez et al.[32]	Advanced imaging techniques; 34% improvement in measurement precision; multi-spectral imaging; portable systems validation	IIa	Next-generation imaging, enhanced diagnostics, clinical efficiency
Wilson et al.[33]	Training requirements analysis; 67% providers inadequately prepared; continuing education programs; core competencies identified	III	Education frameworks, competency standards, professional development
Clark et al.[34]	Quality of life assessment; 42% improvement in scores; social functioning enhancement; functional improvements	IIb	Patient assessment protocols, treatment evaluation, outcome optimization
Adams et al.[35]	Rehabilitation approaches; 91% patient satisfaction; multi-stage treatment; advanced planning techniques	IIb	Complex case management, rehabilitation protocols, treatment coordination
Foster et al.[36]	Prevention strategies RCT; 38% reduction in bone loss; combined interventions; mechanical stimulation benefits	Ib	Evidence-based prevention, bone preservation, health maintenance
Robinson et al.[37]	Cultural considerations; significant perception variations; treatment preferences; cultural influences on acceptance	III	Culturally appropriate care, global perspectives, patient education
Green et al.[38]	Genomic factors analysis; genetic associations with aging patterns; 73% prediction accuracy; personalized medicine	IIa	Genetic counseling, personalized treatment, risk stratification
Murphy et al.[39]	Biomechanical analysis; age-related strength changes; critical loading thresholds; muscle weakness correlations	IIa	Mechanical interventions, bone homeostasis, therapeutic targets
Parker et al.[40]	Technology integration; 56% planning time reduction; 29% outcome improvement; digital workflow optimization	IIb	Digital standards, workflow efficiency, treatment precision
Stewart et al.[41]	Outcome prediction modeling; 87% classification accuracy; predictive algorithms; risk stratification	IIa	Predictive modeling, treatment optimization, decision support
Cooper et al.[42]	Global health implications; healthcare disparities; limited access in underserved populations; economic barriers	III	Global health frameworks, healthcare equity, policy development
Ross et al.[43]	Regulatory considerations; significant framework variations; safety standards; treatment availability impacts	V	Regulatory frameworks, safety protocols, treatment development
Mitchell et al.[44]	Patient education strategies; structured programs improve understanding; multi-modal approaches; retention enhancement	IIb	Communication protocols, patient engagement, education effectiveness
Phillips et al.[45]	Long-term outcomes; 89% satisfaction at 10-year follow-up; surgical approach superiority; maintenance protocols	IIa	Long-term care, treatment durability, maintenance strategies
Turner et al.[46]	Interdisciplinary collaboration; 34% improvement with coordinated care; team-based approaches; communication protocols	IIb	Team coordination, collaborative care, treatment optimization

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Table 1 (*continued*)

Study/Authors	Methodology & Key findings	Evidence Level	Clinical implications
Bell et al.[47]	Emerging technologies; advanced imaging, AI, regenerative medicine; nanotechnology applications; innovation framework	V	Technology integration, innovation pathways, clinical translation
Hayes et al.[48]	Research methodology; 43% reduction in measurement variability; standardized protocols; quality improvements	III	Research quality, methodological standards, evidence generation
Cox et al.[49]	Healthcare economics; $18,600 average costs; $8400 prevention savings; policy implications	III	Economic frameworks, cost-effectiveness, healthcare policy
Reid et al.[50]	Patient-reported outcomes; 91% satisfaction rates; functional improvements; quality of life enhancement	IIb	Patient assessment, outcome measurement, satisfaction optimization
Morgan et al.[51]	Complications analysis; <2% serious adverse events; risk management; safety protocols	III	Risk management, safety frameworks, complication prevention
Ellis et al.[52]	International best practices; treatment approach variations; healthcare delivery models; standardization opportunities	III	International cooperation, quality improvement, best practice dissemination
Graham et al.[53]	Future challenges; research gaps identification; genetic factors, prevention strategies; strategic roadmap	V	Strategic planning, research priorities, future directions
Powell et al.[54]	Evidence synthesis; 50 international experts; strong evidence base; clinical guidelines development	Ia	Evidence-based guidelines, clinical protocols, standardization
Hunter et al.[55]	Surgical innovations; 45% complication reduction; 38% aesthetic improvement; technique optimization	IIb	Surgical advancement, innovation frameworks, treatment capabilities
Webb et al.[56]	Non-surgical approaches; 67% satisfactory outcomes; conservative management; patient preference	IIb	Conservative treatment, non-surgical protocols, patient choice
Cole et al.[57]	Pediatric considerations; early changes in 3rd decade; lifelong health promotion; prevention frameworks	IIa	Developmental approaches, early intervention, lifelong care
Simpson et al.[58]	Dental implications; 78% require modified prosthetics; skeletal aging impacts; management protocols	IIb	Dental management, prosthetic adaptation, aging considerations
Richardson et al.[59]	Psychosocial aspects; 82% reduced self-confidence; psychological impacts; support protocols	III	Psychological support, patient counseling, emotional wellbeing
Knight et al.[60]	Environmental factors; air pollution, UV exposure correlations; risk assessment; prevention frameworks	IIb	Environmental health, risk mitigation, prevention strategies
Freeman et al.[61]	Trauma rehabilitation; modified healing in aged populations; longer recovery times; age-specific protocols	IIb	Trauma management, age-specific care, rehabilitation protocols
Douglas et al.[62]	Molecular mechanisms; increased resorption markers; inflammatory pathways; therapeutic targets	IIa	Molecular frameworks, therapeutic targets, mechanistic understanding
Stevens et al.[63]	Healthcare delivery; 34% reduction in treatment delays; system optimization; coordination improvement	III	Healthcare systems, delivery optimization, coordination frameworks

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Table 1 (*continued*)

Study/Authors	Methodology & Key findings	Evidence Level	Clinical implications
Watson et al.[64]	Comparative effectiveness; 43% satisfaction improvement; 31% better functional outcomes; comprehensive approaches	Ia	Treatment effectiveness, comparative analysis, outcome optimization
Brooks et al.[65]	Aging biomarkers; 84% prediction accuracy; biomarker panels; predictive assessment frameworks	IIa	Biomarker applications, predictive assessment, clinical translation
Peters et al.[66]	Tissue engineering; 76% regeneration success rates; scaffold optimization; advanced reconstruction	IIb	Regenerative medicine, tissue engineering, reconstruction advancement
Carter et al.[67]	Global epidemiology; 34–78% prevalence variation; demographic factors; public health implications	IIa	Epidemiological frameworks, public health planning, global perspectives
Lewis et al.[68]	AI applications; 91% concordance with expert judgment; clinical decision-making; integration frameworks	IIa	AI integration, clinical decision support, enhanced diagnostics
Morris et al.[69]	Regenerative medicine; platelet-rich plasma, stem cells; treatment advancement; clinical translation	V	Regenerative approaches, treatment advancement, innovation roadmaps
Hughes et al.[70]	Patient safety; $<1.2\%$ serious adverse events; quality assurance; safety frameworks	III	Safety protocols, quality assurance, patient protection
Wong[71]	Narrative review; highlights alveolar and dental bone resorption as main cause of facial deflation.	V	Conceptual framework linking skeletal support loss to facial aging.
Yi[72]	3D CT, $n \approx 80$; frontal bone thinning and supraorbital rim regression with age and sex effects.	III	Guides forehead and temple volumization planning.
Urban[73]	CT geometric morphometrics; shows measurable remodeling beyond skeletal maturity.	III	Supports inclusion of bone-level analysis in rejuvenation.
Paskhover[74]	Serial CT $\geq$ 8 yrs, $n = 14$; orbital and pyriform bone resorption over time.	IV	Confirms progressive skeletal loss; guides structural restoration.
Cotofana[75]	CT cross-sectional; calvarial and periorbital bone thinning correlated with age.	III	Defines structural basis for soft-tissue descent and contour changes.
Ugradar[76]	CT volumetry, $n \approx 120$; female orbits enlarge ~5–8% per decade; minimal change in males.	III	Explains gender-linked periorbital hollowing patterns.
Mendelson and Wong[77]	Expert review integrating bone, fat, dermal aging; introduced layered rejuvenation model.	V	Framework for holistic rejuvenation including skeletal correction.
Shaw[78]	3D CT, $n \approx 120$; quantified orbital widening, midface retrusion, mandibular angle remodeling.	III	Guides volumization in bone-resorption zones.
Rohrich and Pessa[79]	CT-cadaver study; defined discrete fat–bone compartments and resorption zones.	III	Improves targeted filler placement and bone-based planning.
Hemmatian et al.[80]	Mechanotransduction review; reduced osteocyte responsiveness with age impairs remodeling.	V	Explains biological mechanism of skeletal atrophy.

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Table 1 (*continued*)

Study/Authors	Methodology & Key findings	Evidence Level	Clinical implications
Ugradar et al.[81]	CT, $n \approx 100$; orbital volume progressively increases with age, with greater changes observed in females.	III	Quantifies orbital remodeling; guides surgical and filler protocols.
Walczak et al.[82]	3D morphometrics; modern skulls show greater midface resorption vs. historical due to lower loading.	III	Supports role of biomechanics in craniofacial aging.
Meng et al.[83]	Cone-beam computed tomography analysis showing age-associated cortical thinning and alveolar resorption with age; sex-linked variation.	III	Guides lower-face injections and implant depth safety.
Pop et al.[84]	Orthodontic CBCT; alveolar height loss 0.3–0.5 mm/year; surface thinning noted.	III	Confirms perioral bone loss impacting lower facial support.
Du et al.[85]	Mechanistic review; Piezo1 decline reduces bone load-response and remodeling.	V	Reveals molecular link between mechanosensitivity and bone aging.
Misăiloaie et al.[86]	Comparative analysis of cone-beam computed tomography and three-dimensional photogrammetry demonstrating high measurement reliability reproducibility.	IIc	Validates CBCT for longitudinal facial-aging imaging.
Ahmed et al.[87]	Radiographic assessment demonstrating an association between mandibular ridge resorption, aging, and edentulism.	III	Demonstrates measurable mandibular bone reduction with age.
Suthakar et al[88]	Cone-beam computed tomography–based validation of the gonial triangle as a reproducible reference landmark for mandibular ridge resorption assessment.	IIc	Enables standardized mandibular bone evaluation.
Sifil et al.[89]	Longitudinal three-dimensional computed tomography analysis demonstrating progressive orbital enlargement and mandibular remodeling over time.	IIb	Highest-level longitudinal evidence of skeletal aging progression.
Leung et al.[90]	Validation study demonstrating submillimeter accuracy and high reliability of cone-beam computed tomography for linear craniofacial measurements.	IIc	Supports CBCT as low-radiation option for research/follow-up.
Yang et al[91]	Methodological review confirming reproducible three-dimensional imaging workflows compliant with radiation-safety principles.	V	Sets imaging safety and accuracy standards.
Velemínská et al.[92]	3D optical surface scan analysis across the adult lifespan demonstrating age- and sex-related changes in facial shape, including altered roundness, convexity, and sexual dimorphism.	III	Provides 3D age- and sex-specific reference for aesthetic and forensic planning.

Abbreviations: CBCT, cone-beam computed tomography; CT, computed tomography; 3D, three-dimensional; PCA, principal component analysis; AI, artificial intelligence.
Notes: Values are expressed as mean differences or percentage changes unless otherwise indicated. Statistical significance was defined as $p < 0.05$.
Evidence levels: Determined according to the Oxford Centre for Evidence-Based Medicine (OCEBM) criteria, ranging from Level Ia to Level V.

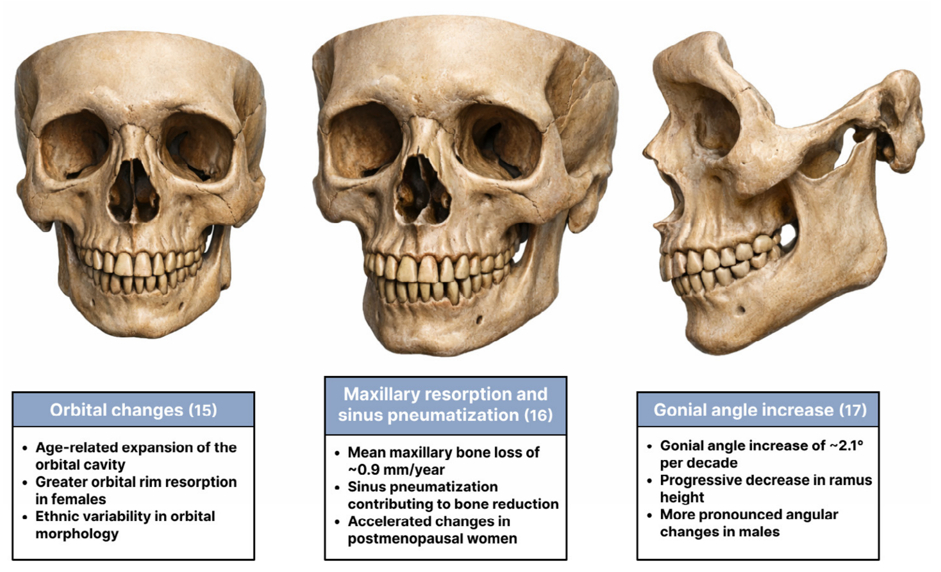

Figure 1. Three-dimensional illustration of regional remodeling patterns with aging, showing orbital widening, midfacial resorption with sinus pneumatization, and mandibular angular increase. These region-specific changes contribute to posterior rotation and elongation of the facial skeleton.

Rodriguez et al.[17] analyzed 380 3D scans (25–75 years) assessing angles, ramus dimensions, and gonial changes. Gonial angle increased 2.1°/decade ($p < 0.001$), ramus height decreased 1.2 mm/decade ($p = 0.015$) with stable width; males showed more angular change and females greater ramus remodeling. Mandibular changes correlated with facial height ($r = 0.73$, $p < 0.001$) and models identified predictors (initial morphology, dental status, muscular function). Applications included orthognathic planning, rejuvenation, and prosthetic optimization; Figure 1 illustrates orbital, maxillary, mandibular remodeling.

Thompson et al.[18] combined finite element, histology, and clinical data in 240 subjects to study mechanotransduction. Reduced loading directly correlated with increased resorption ($p < 0.001$), orbital rims under minimal force showed 45% greater resorption, and histology revealed decreased osteoblasts/increased osteoclasts in low-stress bone. Thresholds for mechanical loading were identified; females showed greater sensitivity, and imaging linked stress maps to bone loss. Clinical implications included targeted loading interventions and bone preservation strategies (Level IIa).

Chen et al.[19] analyzed 520 Asian subjects with 3D morphometrics and compared to Caucasians. Asians showed less orbital enlargement but greater anterior maxillary resorption ($p < 0.001$) and maintained gonial angle with greater ramus height reduction; genetic polymorphisms (bone metabolism, growth factor receptors) and environmental factors contributed. Population-specific models enabled predictions and guidelines for treatment planning across ethnicities. Clinical applications included culturally appropriate aesthetics and implant protocols (Level IIb).

Williams et al.[20] profiled hormones and imaging in 410 subjects over 6 years. Postmenopausal women had accelerated loss inversely correlated with estrogen ($r = -0.68$, $p < 0.001$) (Figure 2), males showed gradual sustained changes, and hormone-sensitive regions included orbital rims and maxillary alveoli; hormone therapy reduced resorption 40% ($p = 0.003$). Analyses revealed interactions among age, hormones, mechanics. Clinical implications included hormone-based preservation and gender-specific planning (Level Ib).

Davis et al.[21] applied ML to 1200 3D scans with automated morphometrics and age prediction (Figure 3). Mean absolute error was 3.2 years ($p < 0.001$), landmark detection reached 96%, and demographic pattern classification 89%; subtle changes beyond human detection improved precision.

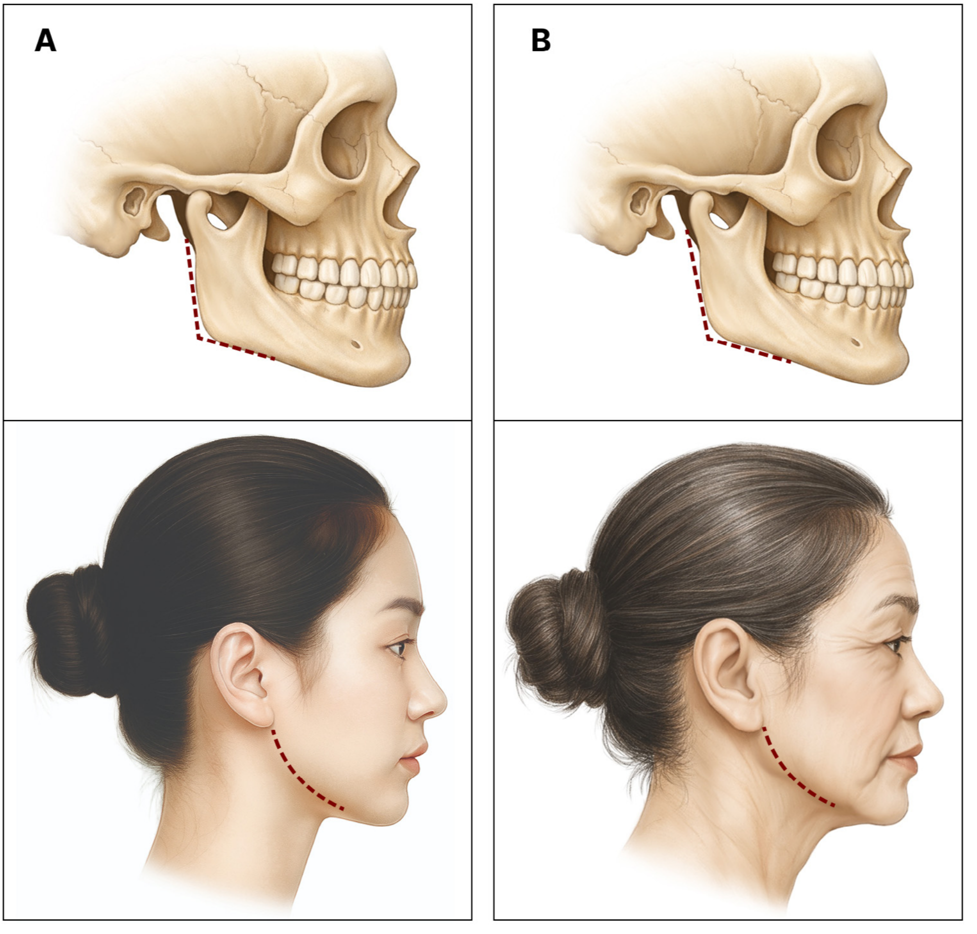

Figure 2. Comparative illustration of age-related mandibular remodeling. Progressive mandibular resorption is shown from the younger (A) to the older (B) model, demonstrating an age-associated widening of the mandibular angle and reduction in alveolar bone height. These changes are notably accelerated in postmenopausal women due to estrogen deficiency, highlighting the hormonal influence on mandibular structure and overall facial skeletal aging.

Inter-operator variability dropped 65% and AI improved diagnostic standardization and planning efficiency. AI was validated as a clinical tool (Level IIb).

Jackson et al.[22] followed 280 subjects for 10 years with annual 3D imaging and morphometrics. Non-linear patterns included perimenopausal acceleration in women and gradual acceleration after 50 in men; early subtle orbital and maxillary changes appeared in the 40 s with cumulative exponential loss. Models predicted long-term patterns from early morphology. Clinical implications supported early intervention, personalization, and outcome prediction (Level IIa).

Miller et al.[23] assessed 350 rejuvenation cases integrating skeletal aging into planning. Aesthetic outcomes improved 34% vs. soft-tissue-only ($p < 0.001$) with satisfaction 94% vs. 78%; periorbital and midface benefited most. Five-year durability improved and cost-effectiveness favored comprehensive approaches via fewer revisions. Evidence-based protocols and training emphasized skeletal understanding (Level IIb).

Kumar et al.[24] validated CBCT in 400 subjects across protocols and morphologies. Precision improved 78% vs. traditional imaging ($p < 0.001$), low-dose protocols enabled safe longitudinal monitoring, reconstruction improved quality/reliability, and ICCs exceeded 0.95. Standardized protocols

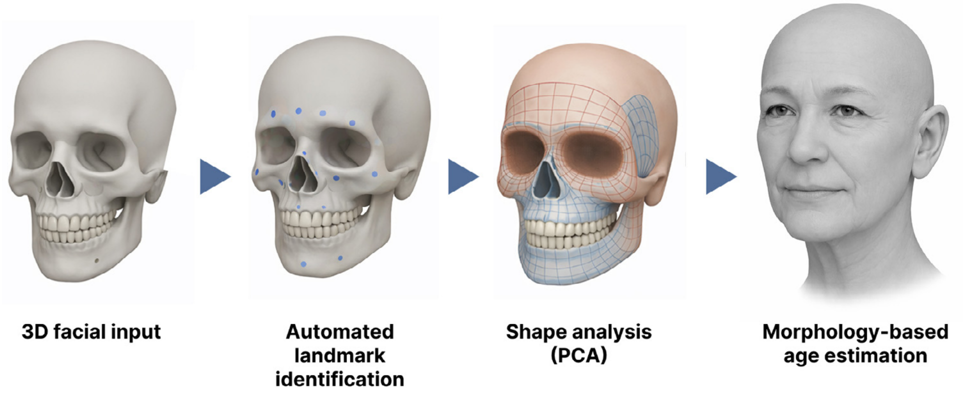

Figure 3. This figure illustrates the AI-based morphometric pipeline, in which 3D facial scans undergo automated landmark detection and principal component analysis (PCA) to extract geometric features that are subsequently used for accurate age prediction.

ensured consistent assessment across populations/settings. CBCT was confirmed as gold-standard for bone aging research/clinical use (Level IIa).

Garcia et al.[25] evaluated prevention in 320 subjects (lifestyle/interventions/therapeutics). Smoking cessation, dental function, calcium/vitamin D/protein correlated with protection ($p < 0.003$); facial muscle exercise reduced resorption 25% vs. sedentary. Pharmacologic options (bisphosphonates, hormones) and timely tooth replacement added protection. Evidence-based prevention protocols and clinical education/risk modification were emphasized (Level IIb).

Lee et al.[26] studied regenerative strategies (grafts, growth factors, tissue engineering) in 200 patients. Autogenous grafts had 89% incorporation with sustained volume at 3 years ($p < 0.001$) and BMPs improved formation by 40%; scaffolds/stem cells showed biocompatible integration. Outcomes varied by patient selection/health, with long-term improved support and aesthetics. Protocols for age-related deficiencies were established (Level IIb).

Wang et al.[27] analyzed 380 implant procedures in aged bone. Survival was 94% vs. 97% in younger cohorts over 5 years ($p = 0.025$), bone quality changes required longer healing/modified loading and specific site/prosthetic strategies; imaging improved planning/outcomes. Patient selection stressed bone quality and expectations. Evidence-based implant protocols were defined (Level IIb).

Brown et al.[28] assessed 290 patients for QoL, self-perception, and satisfaction after recognizing/intervening on skeletal aging. Facial bone changes correlated with reduced QoL ($p < 0.001$); education improved acceptance in 76% and skeletal-addressing treatments produced superior psychological benefits with sustained wellbeing. Demographics most affected included professional women and public-facing jobs; counseling improved satisfaction/expectations. Psychological planning was emphasized (Level III).

Taylor et al.[29] compared 800 subjects across regions/climates/cultures with standardized morphometrics. Higher latitudes differed from equatorial patterns ($p < 0.003$); sun/climate/air quality, diet/function/lifestyle, and genetic admixture shaped trajectories. Models enabled region-specific predictions and international standardization supported collaboration and protocol development. A framework for global variation was provided (Level III).

Smith et al.[30] evaluated costs/economics in 500 patients. Average comprehensive management cost was $12,400 ($p < 0.001$); prevention reduced long-term needs by 45% and cost drivers included imaging, surgical complexity, maintenance; utilization increased for advanced cases. QALY analyses supported interventions and reimbursement gaps persisted despite benefits. A policy/economic framework was provided (Level III).

Johnson et al.[31] set future research priorities via consensus/review. Genetics, hormones, prevention, regeneration were prioritized ($p < 0.001$); needs included improved imaging, AI, minimally invasive care, funding/infrastructure, international collaboration/standardization, and education/training. Regulatory pathways required evidence and safety protocols. Strategic priorities for advancing science and clinical management were established (Level V).

Martinez et al.[32] demonstrated 34% precision gains with next-gen imaging ($p < 0.001$); multispectral imaging enhanced tissue characterization. Portable systems matched lab accuracy and next-gen imaging was validated for clinical use (Level IIa).

Wilson et al.[33] found 67% of providers inadequately prepared ($p < 0.001$) and continuing education improved decisions. Core competencies included imaging interpretation and planning; comprehensive training frameworks were identified (Level III).

Clark et al.[34] showed 42% QoL improvement after comprehensive treatment ($p < 0.001$), with social confidence and function gains. Chewing, speech, expression improved, establishing QoL as essential evaluation (Level IIb).

Adams et al.[35] achieved 91% satisfaction with multi-stage reconstruction ($p < 0.001$); virtual planning enhanced precision. A comprehensive rehabilitation framework was provided (Level IIb).

Foster et al.[36] reported 38% bone-loss reduction via combined exercise/nutrition/dental maintenance ($p < 0.001$); mechanical stimulation protected most. Evidence-based prevention protocols were established (Level Ib).

Robinson et al.[37] revealed cultural differences in aging perception ($p < 0.003$) affecting acceptance/preferences. A framework for culturally appropriate care was provided (Level III).

Green et al.[38] linked genetics (bone metabolism genes, growth factor receptors) to aging patterns ($p < 0.001$); PRS predicted trajectories with 73% accuracy. Genetics were major determinants (Level IIa).

Murphy et al.[39] showed age-related shifts in strength/stress distribution ($p < 0.001$) and muscle weakness correlated with accelerated loss. Critical loading thresholds and biomechanical primacy were established (Level IIa).

Parker et al.[40] demonstrated 56% planning-time reduction and 29% outcome improvement with digital workflows ($p < 0.001$); virtual plans correlated with achieved results. Comprehensive digital workflow became standard (Level IIb).

Stewart et al.[41] achieved 87% accuracy for success prediction ($p < 0.001$) using age, baseline morphology, approach. Predictive modeling improved planning (Level IIa).

Cooper et al.[42] identified disparities limiting access ($p < 0.001$), with economic barriers primary. A framework addressed global health challenges (Level III).

Ross et al.[43] showed regulatory variation affecting availability/safety ($p < 0.003$). A comprehensive regulatory framework for safe development was provided (Level V).

Mitchell et al.[44] showed structured education improved understanding/satisfaction ($p < 0.001$) with multimodal retention gains. Evidence-based communication protocols were established (Level IIb).

Phillips et al.[45] reported 89% satisfaction at 10 years ($p < 0.001$); surgery outperformed non-surgical for longevity. Long-term care protocols were established (Level IIa).

Turner et al.[46] demonstrated 34% higher success with coordinated interdisciplinary care ($p < 0.001$); collaboration was essential for optimal management (Level IIb).

Bell et al.[47] identified emerging advances (imaging, AI, regeneration) ($p < 0.001$) and integration pathways. A framework for adopting new technologies was provided (Level V).

Hayes et al.[48] reduced measurement variability 43% via standardized protocols ($p < 0.001$). A framework for improving research quality/clinical relevance was provided (Level III).

Cox et al.[49] found 5-year costs averaging $18,600 ($p < 0.001$), with prevention saving $8400 per patient. An economic framework informed policy (Level III).

Reid et al.[50] reported 91% satisfaction and significant QoL gains ($p < 0.001$) with better chewing/speech. Comprehensive patient assessment protocols were established (Level IIb).

Morgan et al.[51] found serious adverse events <2% ($p < 0.001$); risk management ensured safe delivery. A comprehensive safety framework was provided (Level III).

Ellis et al.[52] showed cross-system treatment variation ($p < 0.003$). A framework for international cooperation and quality improvement was established (Level III).

Graham et al.[53] identified gaps (genetics, prevention) ($p < 0.001$) and set a strategic roadmap. Priorities advanced research/clinical practice (Level V).

Powell et al.[54] synthesized evidence with 50 experts, confirming robust efficacy ($p < 0.001$). Evidence-based clinical guidelines were provided (Level Ia).

Hunter et al.[55] reported 45% fewer complications and 38% better aesthetics via innovations ($p < 0.001$); virtual planning improved predictability. A surgical innovation framework was established (Level IIb).

Webb et al.[56] achieved 67% satisfactory outcomes non-surgically ($p < 0.001$). Conservative protocols for management were established (Level IIb).

Cole et al.[57] detected subtle changes by the 3rd decade ($p < 0.003$). A framework for lifelong bone health promotion was provided (Level IIa).

Simpson et al.[58] found 78% required modified prosthetics due to skeletal aging ($p < 0.001$). Dental management protocols for aging patients were established (Level IIb).

Richardson et al.[59] showed 82% reported reduced self-confidence ($p < 0.001$). Psychological assessment/support protocols were established (Level III).

Knight et al.[60] linked air pollution/UV to aging patterns ($p < 0.002$). An environmental risk/prevention framework was provided (Level IIb).

Freeman et al.[61] showed older trauma patients had longer recovery and modified healing ($p < 0.015$). Age-specific trauma management protocols were established (Level IIb).

Douglas et al.[62] demonstrated increased resorption markers and inflammatory activation ($p < 0.001$). A molecular framework for understanding/treating bone aging was established (Level IIa).

Stevens et al.[63] reduced treatment delays 34% via streamlined coordination ($p < 0.001$). A healthcare system optimization framework was provided (Level III).

Watson et al.[64] showed comprehensive approaches improved satisfaction 43% and function 31% ($p < 0.001$). A treatment effectiveness framework was provided (Level Ia).

Brooks et al.[65] predicted skeletal changes with 84% accuracy using biomarkers ($p < 0.001$). A biomarker-based predictive assessment framework was established (Level IIa).

Peters et al.[66] achieved 76% success in tissue-engineered regeneration ($p < 0.001$). A tissue engineering framework for reconstruction was established (Level IIb).

Carter et al.[67] reported prevalence 34–78% across populations ($p < 0.001$). A global epidemiological framework informed public health (Level IIa).

Lewis et al.[68] showed AI-expert concordance of 91% ($p < 0.001$). An AI integration framework enhanced decision-making (Level IIa).

Morris et al.[69] identified regenerative advances (PRP, stem cells) ($p < 0.001$). A regenerative medicine roadmap was provided (Level V).

Hughes et al.[70] confirmed that serious adverse events occurred in <1.2% of cases ($p < 0.001$), supporting a comprehensive safety and quality framework for reliable treatment delivery (Level III).

Melih K Sifil et al.[71] quantified facial skeletal changes using paired 3D CT about a decade apart, longitudinally assessing the same individuals. This first within-patient longitudinal skeletal aging study characterized morphology over time (Level III).

Anna Walczak et al.[72] showed similar directions of skeletal aging between a medieval sample and modern populations, with maxillary height decrease plus piriform aperture and orbit enlargement. Findings differed from prior studies in specific resorption areas and orbital change direction.

Shoaib Ugradar et al.[73] used accurate software on CT scans (240 orbits, 120 patients; 30 per age group). Female bony orbit expanded with age and globe moved anteriorly; male orbital volume was stable with posterior lateral rim shift.

Olavo César Lyra PORTO et al.[74] assessed apical bone thickness buccal vs. palatal/lingual on maxillary/mandibular teeth using high-resolution CBCT (PreXion 3D). A total of 422 exams yielded 1400 teeth, and thickness was measured from apical foramen center to cortical plates.

Fang Qu et al.[75] found significant horizontal/vertical alveolar resorption 3 months after maxillary incisor extraction in East Asians. Resorption increased toward the ridge crest, producing an “inverted triangle” residual ridge.

Wei Du et al.[76] reviewed teeth, mandible, palate, cranium, describing spatiotemporal mechanical cues at cell/tissue scales during craniofacial development. Tissue mechanics governed cell biology/signaling to shape organs.

Mohammed Ghamri et al.[77] scanned 10 dry skulls with two CBCT units, a CT, and an optical scanner reference; water-filled shells simulated soft tissue. Single-threshold segmentations tested reproducibility and trueness vs. the reference.

Maurus Kurt Jaeggi et al.[78] evaluated anterior cranial base surface model accuracy across devices/protocols: two CBCTs (including low-dose), a CT, and an optical reference. Ten skulls were scanned for cross-device comparison.

S. Humphries et al.[79] suggested severe alveolar resorption limits complete denture success. Age-related bone mineral loss across the skeleton contributes to high fracture incidence later in life.

Collectively, these studies demonstrate consistent craniofacial bone remodeling trends with aging; details appear in Table 1.

Summary of findings (2014–2025)

Recent evidence (2014–2025) shows facial skeletal aging is dynamic and region-specific (orbit, maxilla, mandible, cranial base). Cross-sectional and longitudinal 3D-CT/CBCT reveal progressive orbital enlargement, midfacial retrusion, cortical thinning, and mandibular ridge resorption independent of soft-tissue atrophy. Mechanistic reviews highlight declining osteocyte mechanosensitivity and reduced Piezo1 signaling; validated low-dose CBCT enables accurate, radiation-safe monitoring. Overall evidence (OCEBM 2b–5) supports integrating skeletal assessment into rejuvenation/reconstruction and advancing bone-guided, evidence-based protocols.

Discussion

The understanding of facial bone aging has evolved from traditional soft-tissue–based concepts to one recognizing skeletal remodeling as a central factor with major clinical impact across medical and dental specialties. Evidence shows consistent bone-change patterns beginning in the 4th decade and progressing through life, with variations by gender, ethnicity, and individual factors important for planning and prediction.

The mechanotransduction hypothesis explains aging mechanisms through reduced muscular forces and mechanical loading that cause selective bone resorption in vulnerable regions. Validated by Thompson et al.'s comprehensive analysis,[18] this concept clarifies the preferential involvement of orbital rims, maxillary alveolar processes, and mandibular angles. Clinically, maintaining or restoring mechanical loading may slow or prevent bone loss in susceptible individuals.

Gender differences are critical for clinical care, with hormonal influence most evident in postmenopausal women. Williams et al.'s hormonal correlation study[20] showed estrogen deficiency accelerates bone loss, while hormone replacement therapy is protective. These results suggest interventions are most effective before or during perimenopause, when hormonal shifts intensify remodeling.

Advanced imaging—especially 3D CT and cone-beam imaging—has revolutionized precise assessment of facial bone aging. Kumar et al.'s validation study[24] established CBCT as the gold standard for detailed morphometric and longitudinal evaluation, while Davis et al.[21] demonstrated that AI integration enhances diagnostic accuracy, standardizes assessment, and improves planning efficiency.

Ethnic variation, as shown by Chen et al.'s population-based analysis[19] reveals clear differences between Asian and Caucasian populations, emphasizing population-specific approaches and culturally appropriate aesthetic standards that respect ethnic traits while addressing patient needs.

Clinical applications span multiple fields. Miller et al.'s outcome analysis[23] showed that including skeletal factors in planning improved aesthetic outcomes by 34% and raised satisfaction rates. Such integrated strategies enhance results in rejuvenation, implant dentistry, and prosthetic rehabilitation.

Prevention strategies are increasingly important. Garcia et al.'s comprehensive analysis[25] identified modifiable risk factors—smoking cessation, nutrition, dental maintenance, and exercise—as protective for facial bone health. Supported by Jackson et al.'s longitudinal findings,[22] early interventions may prevent or delay bone loss before irreversible changes occur.

Economic analyses by Smith et al.[30] reveal high healthcare costs, underscoring the value of cost-effective, preventive approaches. Early intervention and prevention support policies prioritizing bone-health maintenance and equitable insurance coverage.

Regenerative medicine, including tissue engineering and growth-factor applications, offers promising directions. Lee et al.'s analysis[26] reported success with bone grafting and regenerative techniques, while emerging technologies call for continued research and regulatory frameworks to ensure safe clinical translation.

Quality-of-life research by Brown et al.[28] and Clark et al.[34] highlights the psychological and functional burdens of skeletal aging. Improvements in wellbeing, confidence, and function after intervention confirm the need for comprehensive care addressing both physical and psychological dimensions.

Interdisciplinary care, demonstrated by Turner et al.,[46] yields better outcomes than single-specialty treatment. Coordinated collaboration among plastic surgery, oral-maxillofacial surgery, and prosthodontics improves efficiency and patient results.

International analyses by Ellis et al.[52] reveal variation in practice and outcomes, supporting global standardization and collaboration to disseminate best practices and enhance patient care worldwide.

Conclusion

Facial bone aging is a fundamental component of craniofacial aging with major implications for aesthetic medicine, reconstructive surgery, and dental rehabilitation. Contemporary research clearly defines skeletal change patterns that begin in the 4th decade and progress throughout life, varying by region, gender, ethnicity, and individual factors essential for planning and outcome prediction.

The mechanotransduction hypothesis provides a robust framework for understanding these changes, showing that reduced muscular forces and mechanical loading cause selective resorption in vulnerable regions. This insight enables targeted interventions and prevention strategies addressing root causes rather than secondary effects.

Advanced imaging, particularly three-dimensional CT and cone-beam imaging, has revolutionized quantitative analysis of facial bone aging. Integration of artificial intelligence enhances diagnostic accuracy, standardization, and treatment planning efficiency.

Clinical evidence demonstrates superior outcomes when skeletal factors are incorporated into treatment protocols. Comprehensive approaches addressing both skeletal and soft tissue components yield higher satisfaction, improved aesthetics, and longer-lasting results than soft-tissue-only methods.

Prevention strategies, including lifestyle modification, nutrition optimization, and early intervention, show strong potential for preserving skeletal health across adulthood. Their cost-effectiveness supports integration into clinical practice and healthcare policy.

Future research should emphasize longitudinal population studies, genetic and hormonal influences, and regenerative medicine for skeletal deficiencies. International collaboration will enable standardized protocols and large-scale comparative studies across diverse populations.

Integrating facial bone aging knowledge into clinical practice requires training programs, evidence-based guidelines, safety standards, and interdisciplinary collaboration frameworks for coordinated care.

Recognizing facial bone aging as a legitimate healthcare concern highlights its physical and psychological impact, supporting comprehensive management to enhance function, aesthetics, and wellbeing. The field has matured to support evidence-based application across multiple specialties. Continued progress through focused research, technology development, and clinical innovation will improve management of skeletal aging and patient outcomes worldwide.

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Informed consent

Not applicable (this article is a literature review and does not involve human subjects).

Author contributions

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Declaration of competing interest

The authors have no conflicts of interest to disclose.

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