Bone Age Assessment: Methods and Diagnostic Value

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Abstract— **Bone age is a biological marker of skeletal maturation, distinct from chronological age. Its assessment has long relied solely on visual comparison of a left hand and wrist radiograph with the Greulich and Pyle atlas. The last five to seven years have profoundly reshaped this field: meta-analytic demonstration of a systematic ethnic and population-based bias in the classic atlases, the rise of artificial intelligence whose performance masks a still-unresolved methodological circularity problem, and the gradual repositioning of the cervical vertebrae method, long considered the least reliable, as a first-line alternative once its interpretation is automated. Rather than merely juxtaposing the available methods, this review compares them critically, confronts the contradictory findings in the literature according to the populations studied, develops the medico-legal dimension of bone age assessment in light of international recommendations, and proposes a roadmap for Algeria and North Africa, where no national reference standard currently exists.**

Keywords— **bone age, skeletal maturation, Greulich and Pyle, Tanner-Whitehouse, Demirjian, cervical vertebrae, artificial intelligence, forensic age estimation, ethnic bias.**

I. INTRODUCTION

Bone age reflects the true biological maturation of an individual's skeleton, independent of chronological age. Unlike the latter, it incorporates the genetic, hormonal, nutritional, and environmental determinants of skeletal development [1–3]. In clinical practice, its assessment is a first-line diagnostic tool for investigating growth disorders in children, short stature, tall stature, precocious puberty, chronic endocrinopathies [4,5]. Growth delay, more common than growth excess, may result from an endocrine deficiency, a constitutional skeletal disease, a chronic systemic disorder, or a nutritional or psychosocial deficiency [5,6].

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Since the foundational atlas of Greulich and Pyle (1959) [7], numerous methods have been developed, each addressing specific indications, Demirjian's dental method, analysis of cervical vertebral maturation, paranasal sinus pneumatization, particularly useful in orthodontics and forensic medicine [8–12]. More recently, artificial intelligence has introduced automated solutions: between 2019 and 2026, more than thirty primary studies and at least six systematic reviews or meta-analyses have evaluated deep learning models for bone age estimation [13–16], a body of literature that did not exist when earlier North African reviews on this topic were written and that has not yet been validated on a large scale in Algerian or Maghrebi populations.

This is not a simple bibliographic update: the past seven years have reshaped several central assumptions in the field. The supposed universality of the Greulich and Pyle atlas has been directly contradicted by meta-analytic data [13,17]; the reference against which artificial intelligence models are compared has itself become a subject of methodological debate [15,16]; and the cervical vertebrae method is increasingly proposed as a first-line tool once combined with automated interpretation [18,19]. This article pursues three objectives:

1. To synthesize without redundancy the available methods, their indications, and their performance;
2. To critically compare the contradictory data in the literature across ethnicities, across methods, and between the pre- and post-artificial-intelligence eras, rather than merely juxtaposing accuracy figures;
3. To situate this discussion within the medico-legal framework in which bone age estimation is increasingly used, and within the specific needs of Algerian and North African practice, where no national reference standard currently exists.

II. PHYSIOLOGICAL BASIS OF BONE MATURATION

Bone maturation begins during fetal life and ends at the close of adolescence with the fusion of the epiphyseal growth cartilages, in three stages: prenatal maturation (ossification of the diaphyseal primordia; at birth, only the distal femoral, proximal tibial, and proximal humeral ossification centers are visible, with no carpal center yet present); postnatal maturation, with progressive ossification of the tarsus, carpus, long-bone epiphyses, and cranial vault; pubertal maturation, marked by fusion of the growth cartilages. A physiological asymmetry exists between the two limbs, and skeletal maturation generally occurs one to two years earlier in girls than in boys [1], a difference that must systematically be taken into account in interpretation. The main regulators of maturation are growth hormone, thyroid hormones, sex steroids, and IGF-1; a deficiency or excess of any of these results in a delay or advance in bone age.

III. BONE AGE ASSESSMENT METHODS: ANALYTICAL COMPARISON

A.Greulich and Pyle: Historical Reference, Persistent Bias

Published in 1959, the Greulich and Pyle atlas remains the most widely used reference in routine practice3. The method compares an anteroposterior radiograph of the left hand and wrist (ages 0–17 in boys, 0–15 in girls) against age- and sex-specific reference films. Its major structural limitation lies in its reference population: North American children of high socioeconomic status, examined between 1930 and 1950. A 2019 meta-analysis pooling seventeen studies shows that the direction and magnitude of the gap between bone age and chronological age vary systematically by population, with overestimation in certain African, Middle Eastern, and Mediterranean cohorts [13]. A French, Moroccan, Quebec comparison confirms this finding: the atlas performs well in French and Quebec children (mean difference of 0.02 and 0.17 years, $r > 0.93$) but shows an apparent maturational delay in the Moroccan sample (0.6 years, especially in boys, $r = 0.77$) [20], the finding most directly relevant to North African practice, arguing against uncritical application in Algeria.

A systematic review of 51 studies ($n = 19,531$) adds an essential nuance: in Caucasian and Hispanic subjects, the method remains accurate at all ages; in Asian and Arab subjects, both Greulich-Pyle and Tanner-Whitehouse overestimate bone age as adulthood approaches; in sub-Saharan African subjects, only Greulich-Pyle overestimates, while Tanner-Whitehouse remains closer to actual age [21]. This distinction between “Arab” and “African” populations is directly relevant to Algeria, whose population does not fully belong to either category as defined in the existing literature, a further argument against the uncalibrated import of any atlas.

B. Tanner-Whitehouse (TW2/TW3)

Introduced in 1962 and later revised (TW2, TW3), this method individually scores each bone according to standardized stages (A–I), the weighted sum yielding a radius-ulna-short-bone or carpal score4,5,21. More reproducible but considerably more time-consuming, it remains recommended for research and for situations requiring greater precision (hormonal follow-up, forensic medicine). Its better agreement with chronological age in certain African cohorts is not due to a single factor but to two structural differences: Greulich-Pyle relies on an overall comparison to a single reference image, which fully propagates any bias in that reference, whereas Tanner-Whitehouse's bone-by-bone scoring aggregates partially independent assessments, and its data have been recalibrated on more diverse cohorts. The “best” method therefore depends on the population: TW3 is not universally more accurate, but structurally less vulnerable to a single-population bias, though it is not free of bias in Arab subjects nearing adulthood [21]. This precludes recommending it as a universal solution for Algeria without local validation (Section VI.D).

C. Demirjian's Dental Method

Demirjian's method (1973) assesses the mineralization of the seven left permanent mandibular teeth on a panoramic radiograph, classified into eight stages (A–H) [8]. Overall accuracy ≈ 92%, low interobserver variability, applicable from age two, relatively independent of nutritional status, hence its preferred use in orthodontics, maxillofacial surgery, and forensic medicine [8,14]. Its main limitation is the need for population-specific tables [8,21]. Compared to skeletal methods, it is equivalent in reproducibility but generally less accurate in predicting true chronological age, a distinction between precision and accuracy too rarely made explicit in the descriptive literature [21].

D. Cervical Vertebrae Maturation (CVM)

Formalized by Baccetti et al. (2002) [9], this method analyzes the morphology of C2–C4 on lateral cephalometric radiographs, across six stages (CS1–CS6), with stage CS3 corresponding to the pubertal growth peak, the optimal window for orthopedic interventions. The reported manual accuracy (≈82%) has historically been lower than Demirjian's, as the technique remains partly subjective [9]. This has changed since 2023: several studies applying convolutional neural networks to automated scoring report agreement with expert consensus comparable to, or even better than, manual Demirjian scoring, with no additional radiographic exposure beyond the cephalogram already routinely obtained in orthodontics [15,18,19], a development that reshuffles the hierarchy of methods rather than representing a mere marginal gain (Section VI.C).

E. Artificial-Intelligence-Based Automated Methods

BoneXpert, a commercial software based on active appearance modeling, was one of the first automated systems validated in Europe [6]. Since 2019, deep neural networks trained on large public datasets (notably RSNA) have proliferated. A 2025 meta-analysis of 33 studies (2019–2024), predominantly East Asian, reports a weighted mean absolute error of 7.54 months. [15,16]. A parallel review of 26 artificial intelligence studies applied to dento-maxillofacial radiographs reports accuracy reaching 99.98% for bone-age-based models, but substantial heterogeneity related to training data, the reference standard used, and the populations studied [16].

Two recurring limitations are rarely discussed together. First, the vast majority of models are trained and validated against Greulich-Pyle or Tanner-Whitehouse scores assigned by radiologists rather than against an independently verified chronological age: these models therefore learn to reproduce human biases, including any ethnic bias in the reference atlas, rather than to correct them, a circularity problem examined in Section VI.B. Second, nearly all major datasets originate from North American, European, or East Asian populations: the demonstrated accuracy cannot be extrapolated to Algerian or Maghrebi patients without local validation [15,16].

F. Ultrasound

A radiation-free alternative, particularly studied for longitudinal monitoring. A 2025 mini-review synthesizing twenty studies concludes there is a reasonable cross-sectional correlation with radiographic bone age, but wider limits of agreement than radiography, with evidence remaining limited in adolescents nearing skeletal maturity, in the absence of standardized protocols across centers [22]. It is therefore a complementary screening tool, not a substitute for radiography..

G. Paranasal Sinuses

Development of the maxillary, ethmoidal, frontal, and sphenoidal sinuses follow a relatively predictable but variable chronology. Used alone, this method achieves only about 63% accuracy, which rules out its isolated use [10], but it provides useful complementary information after age 18, once dental mineralization is complete [10,12].

Table I.

Analytical Comparison of Bone Age Assessment Methods

Method	Support	Reported accuracy / performance	Reproducibility	Main cross-population limitation
Greulich and Pyle[3],[13],[23]	Hand-wrist, AP view	Variable; overestimation in Africa, Middle East, Mediterranean	Moderate	North American reference population, 1930–1950.
Tanner-Whitehouse (TW2/TW3)[4,5,12,21,22]	Hand-wrist, AP view	Closer to true age in sub-Saharan Africa; also overestimates in Arab subjects nearing adulthood	High	Recalibrated but not validated for Algeria.
Demirjian[8,14,23]	Dental panoramic radiograph	Accuracy ≈ 92%	High	Population-specific conversion tables required
Cervical vertebrae (manual)[9]	Lateral cephalometry	Accuracy ≈ 82%	Moderate	Historically lower than Demirjian.
AI-assisted cervical vertebrae[15,18,19]	Lateral cephalometry	Expert agreement comparable to/ better than manual scoring	High	Limited validation outside East Asian/ European cohorts.
Artificial intelligence (hand-wrist)[15,16]	Hand-wrist, AP view	Mean absolute error ≈ 7.5 months	High	Trained on radiologist-scored age, not true age; limited data diversity.
Ultrasound[22]	Hand-wrist, radiation-free	Moderate-to-good correlation, wider limits of agreement	Variable	Little data in late adolescence; protocols not standardized.
Paranasal sinuses[10,12]	Craniofacial imaging	Accuracy ≈ 63% used alone	Low alone	Useful only as a complement after age 18.

IV. CLINICAL INDICATIONS AND DIAGNOSTIC VALUE

The discordance between bone age and chronological age is the main indication in pediatrics: a bone age lower than chronological age reflects residual growth potential [4,5]. In cases of suspected growth hormone deficiency, the radiograph is integrated into a multimodal work-up (GH, IGF-1, TSH, and prolactin assays; hypothalamic-pituitary MRI to look for a craniopharyngioma, pituitary stalk interruption, or ectopic posterior pituitary) [8,14].

Certain constitutional bone diseases are revealed during the work-up of short stature: brachymetacarpia suggestive of Turner syndrome or pseudohypoparathyroidism, Madelung deformity suggestive of dyschondrosteosis [6,24]. Conversely, early hyperandrogenism or hyperestrogenism leads to advanced maturation, to be investigated in cases of McCune-Albright syndrome, adrenal tumor, or hypothalamic hamartoma [24]. In orthodontics, identifying the pubertal peak (stage CS3) using the cervical vertebrae method optimizes the timing of functional orthopedic treatment; in maxillofacial surgery, assessment of maturity determines the timing of osteotomies, as premature intervention carries a risk of relapse related to residual growth. The combination of Greulich-Pyle (or Tanner-Whitehouse), cervical vertebrae, and Demirjian offers the best accuracy here [3,8,13].

A. Forensic Age Estimation

Bone age estimation has considerable judicial and administrative applications: determining the minority of undocumented individuals, immigration, asylum, and child protection proceedings [2,24]. This is the area where methodological rigor has the most direct consequences for the individuals concerned.

B. International framework.

The Study Group on Forensic Age Diagnostics (AGFAD), founded in 2000 within the German Society of Legal Medicine, issues the most widely followed consensus recommendations for age estimation of living persons in criminal, civil, and asylum proceedings [25,26]. For an individual of potentially minor age and unverified identity, AGFAD recommends a combined approach: physical and pubertal examination (Tanner classification), hand and wrist radiograph, and dental examination with orthopantomogram; once carpal fusion is complete, a CT scan of the medial clavicular epiphysis is added to discriminate between the 18- and 21-year thresholds (Schmeling and Kellinghaus classification) [27,28].

No single method is considered sufficient; AGFAD requires methodological triangulation by examiners trained in forensic medicine in each relevant discipline [26,27]. Comparable frameworks exist within the European Academy of Forensic Science and national forensic medicine societies, with variable implementation and evidentiary weight depending on the jurisdiction.

C. What field data show.

A study of 2,754 forensic expert reports issued by the Institute of Legal Medicine of Catalonia (Barcelona, 2011–2018) illustrates on a large scale the issues specific to North African populations [28]. Among 96.7% male subjects, predominantly of Moroccan (63.6%) and sub-Saharan (19.6%) origin, the protocol applied — Greulich-Pyle, Demirjian, then clavicular CT in the absence of third molars — showed bone-dental agreement in 85.9% of cases. Overall, 28.8% of subjects were estimated to be adults, but with a marked disparity: 86.2% of North Africans were considered minors, compared with only 18% of sub-Saharan Africans. This difference, obtained under a strictly identical protocol, does not by itself prove a methodological bias — it may also reflect a real difference in age structure between populations — but it illustrates why the reference bias documented in Section III is not merely an academic question: since Greulich-Pyle tends to overestimate bone age in African and Arab subjects nearing adulthood [13,21], a misclassification in the direction of adulthood can deprive an actual minor of essential protections.

D. Legal admissibility and the asylum controversy

The central objection is statistical: for a given radiographic appearance, maturation produces a distribution of possible ages, not a single value; any "most likely" estimate therefore carries a wide confidence interval, commonly ±1 to ±2 years, even under the AGFAD protocol, which may well straddle the legal threshold [25,29]. Because the consequences of an error are asymmetric (an adult classified as a minor benefits from protections; a minor classified as an adult, conversely, may be deprived of them — access to asylum protections specific to minors, protection against detention in adult facilities), several learned societies, including pediatric radiology societies, call for age estimation to be used only as one element among others, with any uncertainty resolved in favor of the examinee ("benefit of the doubt") [2,24,29]. The ethnic bias of reference atlases directly worsens this problem for populations not represented in the original cohorts, which is the case for Algerian and Maghrebi populations.

E. Radiation protection.

Since the subjects examined are frequently minors, the principle of justification and optimization of exposure applies with particular force. AGFAD favors a sequence beginning with the least irradiating method, with additional examinations added only in the event of an inconclusive result, using low-dose CT protocols or MRI alternatives for clavicular assessment [2,24,27].

F. Minimum reporting standards.

A forensic report must state: the method(s) used and their published

accuracy in a comparable population; the reference atlas or dataset and its source population; an age range — not a point estimate — together with its uncertainty; and the legal threshold(s) that the conclusion does, or does not, allow to be excluded [25,27,28]. A report providing only a single value, without appropriate reference data or a margin of uncertainty, does not meet these standards.

G. Recommended combinations.

For determinations of adulthood and criminal responsibility, the literature recommends combining hand-wrist radiography, dental assessment, and, once hand fusion is complete, clavicular CT, each method being interpreted using population-appropriate data wherever possible [26,28]. For contexts prioritizing minimization of radiation exposure, MRI of the wrist, knee, or proximal epiphysis has been proposed as an alternative, at the cost of still-limited validation data [2,24].

V. LIMITATIONS AND PERSPECTIVES

The gap between the Greulich-Pyle reference population (North American children, 1930–1950) and contemporary populations remains the main limitation of the classical methods; secular trends in maturation mean that existing atlases may under- or overestimate bone age depending on the population [13,23], and the absence of an Algerian atlas is a persistent source of systematic bias (Section VI.D). Visual interpretation, particularly with Greulich-Pyle, shows documented interobserver variability of around ±6 to ±12 months [4–6]; Tanner-Whitehouse is more objective but time-consuming; the cervical vertebrae method remains sensitive to manual interpretation, though this is improving with automation; artificial intelligence reduces interobserver variability but introduces training-population and circularity problems not yet resolved for non-Western populations.

Current practice favors a combination of indicators depending on context: hand-wrist radiography in general pediatrics, Demirjian and artificial-intelligence-assisted cervical vertebrae assessment in orthodontics and maxillofacial surgery, and paranasal sinuses as a complement [4,5,9]. Forensic applications require a formal methodological combination rather than a single technique (Section V). Ultimately, the diagnostic value of bone age depends on its interpretation within an overall clinical context and on transparent acknowledgment of the reference population used; longitudinal evolution across successive examinations is often more informative than a single measurement [4,5]. Research priorities include prospective validation of artificial intelligence tools against documented chronological age (rather than against expert scores), further validation of ultrasound in late adolescence, and, for Algeria and neighboring countries, the construction of a national, multi-method reference dataset.

VI. CONCLUSION

Bone age remains an indispensable biological marker of skeletal maturation, central to diagnostic and therapeutic decisions in pediatrics, orthodontics, maxillofacial surgery, and forensic medicine. Greulich-Pyle remains the most widely used approach despite a now well-documented reference-population bias; Demirjian remains an approach of choice in craniofacial imaging and forensic estimation; and the cervical vertebrae method, long the least accurate of the radiographic techniques, is being repositioned by artificial-intelligence-assisted scoring as a potentially preferred tool in orthodontics. The past seven years of literature converge on a single conclusion: reported accuracy figures are not transferable from one population to another, and neither conventional atlases nor their artificial-intelligence-based successors should be presumed valid for a population in which they have not been locally tested. Interpretation of bone age must always take into account sex, ethnic origin, and clinical context, as well as, in the forensic context, the margin of uncertainty imposed by international recommendations. Developing a multi-method reference standard specific to the Algerian and North African population, combined with locally validated artificial intelligence tools, is the central research priority for improving the accuracy, fairness, and forensic admissibility of bone age assessment in the regional healthcare context.

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