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Craniofacial Soft Tissue Thickness in Indian Populations: A Systematic Review and Meta-Analysis with Global Forensic Comparisons

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Abstract

Objectives: The present study aimed to systematically review and meta-analyze craniofacial soft tissue thickness (CFSTT) data in Indian populations and compare these findings with global datasets to evaluate biological variation and forensic relevance in facial reconstruction and human identification.

Methods: A systematic review was conducted according to PRISMA guidelines. Electronic searches were performed in PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, and Google Scholar for studies reporting quantitative CFSTT measurements in adult populations. Observational studies using radiological, anthropometric, or postmortem measurement techniques were included. Data were extracted on study characteristics, imaging modality, anatomical landmarks, and CFSTT values. Random-effects meta-analysis was performed, and subgroup analyses were conducted based on sex, age, geographic region, and imaging modality.

Results: From 1,842 identified records, 43 studies met the eligibility criteria, including 23 Indian and 20 international investigations. Thirty-five studies provided sufficient data for meta-analysis. Indian populations demonstrated greater midfacial and perioral soft tissue thickness than European and East Asian groups, while values were comparable to Mediterranean populations and slightly lower than those observed in African populations. Significant sexual dimorphism was observed, with males exhibiting higher CFSTT values than females. Peak thickness occurred during middle adulthood, and CT and CBCT imaging produced the most reliable measurements.

Conclusion: Indian populations exhibit distinct craniofacial soft tissue patterns requiring population-specific forensic reference standards to improve facial reconstruction and human identification accuracy.

Highlights

• A comprehensive systematic review and meta-analysis of craniofacial soft tissue thickness (CFSTT) in Indian and global populations was conducted following PRISMA guidelines.

• Forty-three studies (23 Indian and 20 international) were synthesized, with 35 providing quantitative data for pooled statistical analysis.

• Indian populations demonstrated significantly greater midfacial and perioral soft tissue thickness compared with European and East Asian groups.

• Pronounced sexual dimorphism and age-related variation were observed, with males showing higher CFSTT values and peak thickness occurring in middle adulthood.

• Computed tomography (CT) and cone-beam computed tomography (CBCT) were identified as the most reliable modalities for forensic CFSTT measurement.

• Population-specific CFSTT reference standards substantially improve the accuracy of forensic facial reconstruction and biological profile estimation.

• Integration of artificial intelligence and nationally standardized databases represents a promising direction for future forensic identification systems.

1. Introduction

Craniofacial soft tissue thickness (CFSTT) refers to the distance between the external skin surface and the underlying cranial bone at standardized anatomical landmarks [1]. These measurements form the anatomical basis of forensic facial approximation, craniofacial identification, and medico-legal facial profiling [2]. Quantitative CFSTT data enable forensic experts to reconstruct facial morphology from skeletal remains, thereby assisting human identification in criminal investigations, disaster victim identification, and missing persons cases [1–3]. Forensic facial reconstruction is based on the principle that predictable relationships exist between skeletal morphology and the overlying soft tissues [4]. Accurate estimation of these relationships improves the morphological fidelity of reconstructed faces and enhances their recognition potential in investigative contexts [4–6]. Consequently, the availability of population-specific and methodologically reliable CFSTT reference data is essential for modern forensic practice. The scientific basis of facial reconstruction was established during the early twentieth century through the pioneering work of Gerasimov, who introduced systematic anatomical methods for reconstructing facial features from skeletal remains using average tissue-depth measurements derived from anatomical dissections [6, 7]. Subsequent advances in radiological imaging significantly improved measurement accuracy and reproducibility. The introduction of computed tomography (CT) and magnetic resonance imaging (MRI) enabled non-invasive in vivo measurement of facial soft tissues and

facilitated the development of large radiological CFSTT databases across Europe, East Asia, and North America [8–12]. Craniofacial soft tissue thickness is influenced by several biological and environmental factors. Sexual dimorphism is consistently reported across populations, with males generally demonstrating greater tissue thickness at most craniofacial landmarks due to differences in skeletal morphology and muscular development [13, 14]. Age-related variation is another important determinant, as progressive changes in subcutaneous fat distribution, muscle tone, and dermal elasticity occur throughout the lifespan [15, 16]. Additionally, body mass index (BMI), nutritional status, and lifestyle factors may influence facial soft tissue thickness, particularly in the buccal and mandibular regions [16, 17].

A key principle in forensic anthropology is that craniofacial standards should be population-specific. Numerous studies have demonstrated substantial inter-population variation in CFSTT values, reflecting differences in genetic background, environmental influences, and lifestyle characteristics [18–21]. European populations generally exhibit thinner midfacial tissues than African and South Asian populations, whereas East Asian populations exhibit distinct patterns of nasal and perioral soft-tissue thickness [22–24].

1.2 Aim and Objectives of the Present Study

The present study aims to systematically review and meta-analyze craniofacial soft tissue thickness data from Indian populations and to compare these findings with established global datasets.

The specific objectives are to:

1. To systematically review published literature reporting craniofacial soft tissue thickness measurements in Indian and global populations using radiological and anthropometric methods.
2. To perform a meta-analysis to determine pooled mean CFSTT values for major craniofacial landmarks commonly used in forensic facial reconstruction.
3. To evaluate sexual dimorphism in craniofacial soft tissue thickness across different craniofacial regions.
4. To assess age-related variation in facial soft tissue thickness patterns across adult age groups.
5. To compare CFSTT values between Indian and global populations, identifying population-specific differences relevant to forensic identification.
6. To examine the influence of measurement modality (e.g., CT, CBCT, MRI, cephalometry) on reported CFSTT values.

2. Material and methods

2.1 Study design and ethical aspects

This study was conducted as a systematic literature review and meta-analysis following the recommendations of the Enhancing the Quality and Transparency of Health Research (EQUATOR) network. Accordingly, the methodological framework was established in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [19]. A preliminary protocol outlining the objectives, eligibility criteria, and analytical procedures was developed prior to the initiation of the review process to enhance transparency and methodological rigor. Because the study was based exclusively on previously published data, ethical approval and informed consent were not required. The study followed internationally accepted standards for systematic evidence synthesis and adhered to the methodological recommendations for observational studies in epidemiology.

2.2 Research question and eligibility criteria

The research question was formulated using the CoCoPop framework, which is recommended for systematic reviews addressing prevalence and epidemiological outcomes. Within this framework, the population (Pop) comprised adult human populations, the condition (Co) corresponded to craniofacial soft tissue thickness measurements, and the context (Co) referred to radiological or anatomical evaluation of facial soft tissues in forensic and anthropological research.

Accordingly, the research question guiding the present review was:

“What are the craniofacial soft tissue thickness values reported in Indian populations and how do they compare with global datasets used for forensic facial reconstruction? “The inclusion criteria consisted of observational studies reporting quantitative measurements of craniofacial soft-tissue thickness obtained via radiological imaging techniques such as computed tomography (CT), cone-beam computed tomography (CBCT), magnetic resonance imaging (MRI), cephalometric radiography, or ultrasonography. Studies were included when they reported CFSTT values for clearly defined craniofacial landmarks in adult human populations. The exclusion criteria comprised experimental studies, animal studies, studies based solely on dry skull specimens without soft tissue measurements, case reports, case

series, editorials, letters to the editor, conference abstracts, book chapters, dissertations without accessible data, and research protocols. Studies that did not provide quantitative CFSTT measurements or lacked sufficient methodological information were also excluded. No restrictions were applied regarding language, publication year, or publication status.

2.3 Data sources and search strategy

A comprehensive literature search was performed in multiple electronic databases to identify relevant studies. The databases searched included Medline/PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. To minimize publication bias, grey literature sources were also screened where possible.The search strategy was developed using a combination of Medical Subject Headings (MeSH), Descriptors in Health Sciences (DeCS), and relevant free-text keywords related to three conceptual domains: craniofacial anatomy (e.g., craniofacial soft tissue thickness, facial soft tissue), imaging modality (e.g., computed tomography, CBCT, MRI, radiography), and forensic application (e.g., facial reconstruction, forensic anthropology, morphometry). Synonyms and alternative terminology were incorporated within each domain.Boolean operators (“AND” and “OR”) were used to combine the search terms. The complete search strategy applied to each database is presented in Table 1. The initial search was conducted in March 2025, and an updated search was performed in November 2025 to ensure the inclusion of recently published studies.

Table 1
Search strategies applied to screen studies in the databases.

Database	Strategy
Medline / PubMed	("craniofacial soft tissue thickness"[Title/Abstract] OR "facial soft tissue thickness"[Title/Abstract] OR "CFSTT"[Title/Abstract]) AND ("computed tomography"[Title/Abstract] OR "CT"[Title/Abstract] OR "cone beam"[Title/Abstract] OR "CBCT"[Title/Abstract] OR "MRI"[Title/Abstract] OR "radiography"[Title/Abstract] OR "imaging"[Title/Abstract]) AND ("facial reconstruction"[Title/Abstract] OR "forensic identification"[Title/Abstract] OR "forensic anthropology"[Title/Abstract] OR morphometry[Title/Abstract] OR anatomy[Title/Abstract])
Scopus	TITLE-ABS-KEY (("craniofacial soft tissue thickness" OR "facial soft tissue thickness" OR CFSTT) AND ("computed tomography" OR CT OR "cone beam" OR CBCT OR MRI OR radiography OR imaging) AND ("forensic facial reconstruction" OR "forensic identification" OR morphometry OR anatomy))
Web of Science	TS = (("craniofacial soft tissue thickness" OR "facial soft tissue thickness" OR CFSTT) AND ("computed tomography" OR CT OR "cone beam computed tomography" OR CBCT OR MRI OR radiography OR imaging) AND ("forensic facial reconstruction" OR "forensic anthropology" OR morphometry OR anatomy))
ScienceDirect	("craniofacial soft tissue thickness" OR "facial soft tissue thickness" OR CFSTT) AND ("computed tomography" OR CT OR "cone beam computed tomography" OR CBCT OR MRI OR radiography OR imaging) AND ("facial reconstruction" OR "forensic identification" OR morphometry OR anatomy)
Google Scholar	("craniofacial soft tissue thickness" OR "facial soft tissue thickness") AND ("computed tomography" OR "cone beam computed tomography" OR CBCT OR MRI) AND ("forensic facial reconstruction" OR "forensic anthropology")

2.4 Study selection

Study selection was performed independently by two reviewers with prior experience in forensic anthropology, craniofacial morphometry, forensic radiology, and systematic review methodology. Reviewer 1 has extensive experience in craniofacial soft tissue thickness (CFSTT) research and forensic facial reconstruction, while Reviewer 2 has expertise in forensic imaging, craniofacial morphometric analysis, and evidence synthesis. Prior to formal screening, both reviewers underwent calibration using a pilot sample of 50 randomly selected records to ensure uniform interpretation of eligibility criteria. Inter-reviewer agreement was assessed using Cohen’s kappa statistic, and screening proceeded only after substantial agreement ($\kappa > 0.80$) was achieved. Any disagreements during title screening, abstract assessment, or full-text evaluation were resolved through discussion and, when necessary, consultation with a third senior reviewer experienced in forensic anthropology and forensic radiology.

2.5 Data extraction

For each eligible study, relevant information was extracted using a standardized data extraction form. The following variables were recorded: author names, year of publication, country of study, sample size, demographic characteristics of the study population, imaging modality used, anatomical landmarks evaluated, and reported craniofacial soft tissue thickness values.Additional information on sex-specific measurements, age distribution, and methodological details of measurement procedures was also collected when available. Data extraction was performed independently by two reviewers, and discrepancies were resolved by consensus with a third reviewer. Extracted data were summarized descriptively for qualitative synthesis. Once sufficient homogeneity in measurement reporting was identified, a quantitative meta-analysis was conducted to generate pooled estimates of craniofacial soft-tissue thickness. To improve comparability across studies, craniofacial landmarks reported under different terminologies were harmonized according to the standardized nomenclature proposed by Caple and Stephan (2016). When multiple studies used different names for equivalent anatomical locations, a single standardized term was adopted for data extraction and synthesis. Definitions of all craniofacial landmarks included in the review are

provided in Supplementary Table S2, which lists landmark names, abbreviations, anatomical definitions, and corresponding alternative terminology reported in the literature.

2.6 Assessment of Risk of Bias

The methodological quality of the included studies was assessed using a critical appraisal checklist adapted for observational studies reporting prevalence or morphometric measurements. Each study was evaluated across several methodological domains, including sampling strategy, measurement reliability, clarity of anatomical landmark definitions, completeness of data, and transparency of reporting. The appraisal approach followed established methodological recommendations for systematic reviews of observational research and morphometric data [21]. Two independent reviewers performed the quality assessment, and disagreements were resolved through discussion and consultation with a third reviewer when necessary. Each checklist item was scored as “yes”, “no”, “unclear”, or “not applicable”, in accordance with commonly used critical appraisal frameworks for epidemiological studies [22]. The overall methodological quality of each study was determined based on the proportion of positive (“yes”) responses obtained across the checklist items. Studies were subsequently categorized into three levels of risk of bias:

- Low risk of bias: ≥70% positive responses
- Moderate risk of bias: 50–69% positive responses
- High risk of bias: ≤49% positive responses

Items marked as “not applicable” or “unclear” were excluded from the denominator when calculating the percentage of positive responses to ensure that only relevant methodological criteria were considered. This approach is consistent with previously published systematic reviews evaluating morphometric and forensic anthropological datasets [21]. The risk-of-bias evaluation enabled identification of potential methodological limitations within the literature and allowed the inclusion of sensitivity analyses assessing the impact of lower-quality studies on pooled estimates.

2.7 Statistical analysis

Meta-analysis was conducted using R statistical software (version 4.3.2; R Foundation for Statistical Computing, Vienna, Austria). Pooled estimates of craniofacial soft tissue thickness (CFSTT) were calculated using a random-effects model with the DerSimonian–Laird estimator, which accounts for both within-study and between-study variability. Heterogeneity among studies was evaluated using Cochran’s Q test and the I^2 statistic, where I^2 values of approximately 25%, 50%, and 75% were interpreted as indicating low, moderate, and high heterogeneity, respectively. Subgroup analyses were performed according to sex, age group, geographic population, and imaging modality. Sensitivity analyses were conducted using a leave-one-out approach to evaluate the influence of individual studies on pooled estimates. Potential publication bias was assessed through visual inspection of funnel plots and Egger’s regression test, with statistical significance defined as $p < 0.05$.

3. Results

3.1 Study selection and PRISMA flow

The systematic database search identified 1,842 records. After removal of 436 duplicate articles, 1,406 unique records remained for screening. Title and abstract screening resulted in the exclusion of 1,267 records that did not meet the predefined eligibility criteria. Full-text assessment was conducted for 139 articles, of which 96 were excluded due to incomplete data, absence of adult samples, unclear methodology, or lack of standardized craniofacial landmarks. Ultimately, 43 studies fulfilled all inclusion criteria and were included in the qualitative synthesis. Among these, 23 studies represented Indian populations and 20 represented global populations. A total of 35 studies (18 Indian and 17 international) provided sufficient quantitative data and were included in the meta-analysis (Fig. 1). The characteristics of Indian population studies included in the meta-analysis are summarized in Table 2. The global studies included for comparative analysis are detailed in Table 3.

Table 2
Indian Population Studies Included in Meta-Analysis on Facial Soft Tissue Thickness

S. No.	Author (Year)	Region / Population	Sample Size (M/F)	Age Range (yrs)	Imaging / Method	No. of Landmarks	Key Data Used in Review / Meta-analysis	Forensic Significance
1	Battan et al. (2025) [25]	Northwest India	1306 (650/656)	18–80	CT (MDCT)	20	Large-scale CFSTT + fat layer dataset; strong CFSTT–fat correlation (R^2 = 0.938); DFA > 90%	Primary reference for facial approximation and sex estimation
2	Jayakrishnan et al. (2025) [26]	Pan-India	450	Adults	CBCT	28	Sexual dimorphism; ANN accuracy ~ 99%	Supports AI-based forensic identification
3	Nongmeikapam et al. (2025) [27]	Northeast India	70 (35/35)	20–55	CT	26	Regional CFSTT norms	Enables accurate regional reconstruction
4	Sravani et al. (2025) [28]	Southeast India	60	18–70	MRI	12	MRI-based baseline values	Non-invasive forensic imaging
5	Gupta et al. (2012) [29]	North India	120	18–28	Cephalogram	19	Nasal prominence, lip thickness, H-angle	Population-specific soft tissue norms
6	Kunnath et al. (2020) [30]	South India	88	Adults	CBCT	24	Sexual dimorphism; bilateral symmetry	Improves bilateral reconstruction accuracy
7	Thakur & Sehrawat (2023) [31]	North India	120 (57/63)	20–65	MRI	21	Age-related variation	Supports age-adjusted reconstruction
8	Guleria et al. (2025) [32]	North India (Chandigarh)	228 (158/70)	18–35	Photography + Anthropometry	12	Facial and nasal indices; phenotypes	Biometric and medico-legal profiling
9	Chetal et al. (2023) [33]	Central India	100	18–50	Cross-sectional	12	Facial height–stature correlation	Sex and stature estimation
10	Meundi & David (2019a) [34]	South India	80 (40/40)	Adults	CBCT	34	CBCT-based norms	High-resolution reference values
11	Meundi & David (2019b) [35]	South India	90 (45/45)	18–35	CBCT	34	Skeletal class variation	Individualized modelling
12	Kundu et al. (2025) 36]	East India	65 (32/33)	22–58	CT	24	Regional CFSTT norms	Region-specific reconstruction
13	Samuel (2021) [37]	South India (Kerala)	144 (72/72)	21–60	Autopsy	21	Postmortem norms	Validation for decomposed remains
14	Lodha et al. (2016) [38]	South India (Gujarat)	308	18–27	Cephalogram	23	BMI and sex-related variation	Nutritional correction
15	Jain et al. (2016) [39]	North India	300 (150/150)	18–50	Dry crania	10	Cranial metrics	Indirect sex estimation
16	Sachan et al. (2012) [40]	North India	60 (30/30)	18–35	Cephalogram	11	Soft tissue norms	Orthodontic–forensic linkage
17	Maini et al. (2011/2012) [41]	North India	40	18–60	Spiral CT	10	Soft tissue norms	Thickness decreases with age; significantly

S. No.	Author (Year)	Region / Population	Sample Size (M/F)	Age Range (yrs)	Imaging / Method	No. of Landmarks	Key Data Used in Review / Meta-analysis	Forensic Significance
								lower in females
18	Nitya et al (2022) [42]	South India (Karnataka)	200 (100/100)	18–30	Cephalogram	11	Ethnic-specific norms for Lambani vs. Kannadiga	efines reconstruction for specific tribal and regional subgroups
19	Saxena et al. (2012) [43]	North India	40 (19/21)	18–25	Cephalogram	—	Ethnic norms	Population-specific modelling
20	Sahni et al. (2014) [44]	North India	300 (173/127)	18–70	Anthropometry	15	Facial variability	Soft-tissue prediction
21	Gupta et al. (2014) [45]	North India	120 (60/60)	18–28	Photos + Cephalogram	17	Aesthetic norms	Improves facial likeness
22	Sahni et al. (2008) [46]	Northwest India	300 (173/127)	20–60	MRI	29	First MRI CFSTT dataset	Foundation for Indian standards
23	Trivedi et al. (2010) [47]	Rajasthan	200	18–25	Cephalogram	15	Regional norms	Regional forensic databases

Table 3
Global Population Studies on Facial Soft Tissue Thickness with Forensic Significance

S. No.	Author (Year)	Country / Population	Sample Size (M/F)	Age Range (yrs)	Imaging / Method	No. of Landmarks	Key Data Used in Review / Meta-analysis	Forensic Significance
1	Simpson & Henneberg, 2002 [8]	Australia	100	Adults	Caliper / Radiography	22	FSTT–craniometric correlation	Early predictive models
2	De Greef et al., 2006 [21]	Belgium (Caucasian)	700+	18–75	CT	52	Large in vivo database	European reference dataset
3	Smith & Throckmorton, 2006 [48]	USA	60	Adolescents–Adults	X-ray / Ultrasound	14	Method comparison	Non-invasive validation
4	Hwang et al., 2012 [23]	Korea	118	Adults	CT	31	National database	East Asian standard
5	Utsuno et al., 2010 [49]	Japan	60 (F)	Adults	CT	17	Skeletal class variation	Class-adjusted modelling
6	Cavanagh & Steyn, 2011 [50]	South Africa (Females)	90 (F)	Adults	CT	20	Female-specific norms	Sex-specific reconstruction
7	De Almeida et al., 2013 [51]	Brazil	150	Adults	CT	32	New landmark standards	Latin American baseline
8	Guyomarc'h et al., 2013 [52]	France	400	Adults	3D CT	35	Population variability	Individualized modelling
9	Adegbite et al., 2025a [43]	Nigeria (Males)	110 (M)	Adults	CT	20	High-resolution male data	Improved accuracy
10	Stephan, 2015 [06]	Australia (Review)	—	—	Meta-analysis	—	Accuracy assessment	Method validation
11	Ayoub et al., 2019 [53]	Mediterranean	120	Adults	CT	15	Midsagittal norms	Profile reconstruction
12	Beaini et al., 2021 [54]	Brazil	200	Adults	CBCT	36	Living-subject dataset	Modern reference
13	Wang et al., 2022 [55]	China (Han)	180	20–70	CT	24	Age-related variation	Age-adjusted models
14	Dong et al., 2012 [56]	China (Northern Han)	150	Adults	CT	25	BMI influence	Weight correction
15	Paneková et al., 2012 [57]	Slovakia	90	Adults	CT	18	Midface norms	Central European reference
16	Codinha, 2009 [58]	Portugal	100	Adults	CT	21	Adult database	Iberian standards
17	Thiemann et al., 2017 [59]	Germany	400+	Adults	CT	42	Large in vivo dataset	Reliable European data
18	Te Wai Pounamu et al., 2023 [50]	Global	90 + studies	Mixed	Meta-analysis	—	Pooled values	Global benchmarks
19	Adegbite et al., 2025b [43]	Nigeria (Males)	220 (M)	Adults	CT	50	Male-specific dataset	Ancestry estimation
20	Hona & Stephan, 2022 [60]	Global	—	—	Review	—	Landmark standardization	Reduces error
21	Meikle & Stephan, 2020 [47]	Australia	60	Adults	Ultrasound	18	Standard protocol	Field measurements

S. No.	Author (Year)	Country / Population	Sample Size (M/F)	Age Range (yrs)	Imaging / Method	No. of Landmarks	Key Data Used in Review / Meta-analysis	Forensic Significance
22	Tanaka et al., 2020 [61]	Japan	120	Adults	PMCT	26	Postmortem CT dataset	DVI applications

3.2 General characteristics of included studies

3.2.1 Indian studies

The Indian studies included in the present meta-analysis comprised a total of 4,812 individuals, including 2,394 males and 2,418 females, with ages ranging from 18 to 80 years. A variety of imaging and measurement techniques were employed across the included investigations, reflecting the methodological diversity of craniofacial soft tissue thickness (CFSTT) research in India. Computed tomography (CT) was the most frequently utilized modality, accounting for seven studies, followed by cone-beam computed tomography (CBCT) in six studies, magnetic resonance imaging (MRI) in four studies, and cephalometric radiography in four studies. Additionally, one study employed post-mortem needle puncture techniques for direct tissue thickness assessment. The number of craniofacial landmarks evaluated varied considerably among studies, ranging from 10 to 50 anatomical points, although most investigations focused on commonly used midline and bilateral landmarks relevant to forensic facial reconstruction. Notably, the large-scale datasets reported by Battan et al. and Jayakrishnan et al. contributed substantially to the overall evidence base and collectively represented more than one-third of the total Indian sample included in the review. The broad geographic coverage, large cumulative sample size, and diversity of imaging modalities provide a comprehensive overview of CFSTT variation within Indian populations. Detailed characteristics of the included Indian studies are presented in Table 2.

Section 3.2.2 Modality Discussion

Device-related variability represents an additional source of heterogeneity among the included studies. CT-based investigations employed scanners from different manufacturers, including Siemens, GE Healthcare, Philips, Toshiba, and Canon systems, with acquisition parameters varying substantially across studies. Reported slice thicknesses ranged from 0.5 mm to 5 mm, while tube voltages typically varied between 100 and 140 kV. Previous studies have demonstrated that thinner slice thicknesses improve landmark localization accuracy and reduce partial-volume effects, particularly in anatomically complex regions such as the nasal, orbital, and mandibular areas. Conversely, larger slice thicknesses may reduce measurement precision and increase observer variability.

Similarly, CBCT studies differed in voxel size, field of view, detector characteristics, and reconstruction algorithms, all of which may influence soft tissue visualization and measurement accuracy. MRI studies also varied in magnetic field strength (1.5 T versus 3 T), pulse sequence selection, and image resolution. These methodological differences likely contributed to the substantial heterogeneity observed across studies and should be considered when interpreting pooled estimates.

A major advantage of cephalometric radiography is its standardized imaging geometry and predictable magnification factor (approximately 110%), which permits reliable linear measurements and has contributed to its long-standing use in orthodontic diagnosis, craniofacial assessment, and forensic investigations. However, because cephalograms are two-dimensional representations of three-dimensional structures, superimposition of anatomical features may limit landmark visualization in certain regions.

Although ultrasonography is non-invasive, inexpensive, and free from ionizing radiation, its principal limitation for CFSTT assessment is the difficulty in accurately localizing underlying skeletal landmarks. In addition, ultrasound measurements are highly operator-dependent and may be influenced by transducer positioning and tissue compression during image acquisition. These factors may reduce measurement reproducibility and contribute to inter-study variability. Although ultrasonography is non-invasive and free from ionizing radiation, its principal limitation for CFSTT assessment is difficulty in accurately localizing underlying skeletal landmarks, which may reduce measurement reproducibility.

3.2.3 Global studies

The global dataset comprised approximately 7,950 individuals drawn from European, African, East Asian, South American, and Mediterranean populations. Numerous international studies have established large radiological databases of craniofacial soft tissue thickness (CFSTT), contributing substantially to the development of forensic facial reconstruction standards across different populations. These datasets provide important comparative frameworks for evaluating population-specific craniofacial soft-tissue patterns [21, 23, 84]. The global studies included for comparative analysis are detailed in Table 3. Among the included studies, computed tomography (CT)–based investigations predominated (n = 11), reflecting the increasing use of high-resolution three-dimensional imaging in craniofacial

morphometric research. Other methodologies included cone-beam computed tomography (CBCT) (n = 4), ultrasonography (n = 2), and post-mortem computed tomography (PMCT) (n = 2). CT-based measurement approaches have been widely recognized for providing accurate and reproducible in vivo measurements of facial soft tissues and are commonly used in contemporary forensic identification research [21, 23, 82–84].European investigations contributed some of the largest CFSTT datasets, particularly those reported from Belgium, France, Portugal, Slovakia, and Germany, which collectively provide extensive reference values for Caucasian populations [21, 80, 82, 83, 84]. In contrast, East Asian studies from Korea, Japan, and China have produced detailed analyses of nasal and midfacial soft tissue thickness, including investigations examining the influence of skeletal class, age, and body mass index on facial soft tissue distribution [23, 77, 84].

Overall, global studies generally incorporated a larger number of anatomical landmarks and demonstrated greater methodological standardization compared with many regional investigations conducted within India. Large-scale international datasets and meta-analytical studies have emphasized the importance of standardized craniofacial landmark definitions and imaging protocols to improve the reproducibility of CFSTT measurements used in forensic facial approximation [50]. Figure 2 illustrates the geographical distribution of CFSTT research included in the present review. The figure demonstrates extensive global coverage across Europe, East Asia, Africa, and the Americas, whereas Indian studies were primarily concentrated in North, South, Northwest, East, and Northeast India, with limited representation from Central India. This uneven geographical distribution highlights the need for comprehensive national CFSTT datasets to support forensic identification and facial reconstruction research within the Indian population [24, 25]. A summary of overall study characteristics across Indian and global datasets is presented in Table 4.

Table 4
Summary Characteristics of Included Studies.

Variable	Indian Studies	Global Studies	Total
Number of studies	23	20	43
Total sample size	4,812	7,950	12,762
Male participants	2,394	—	—
Female participants	2,418	—	—
Age range	18–80 yrs	18–75 yrs	Adult populations
CT-based studies	7	11	18
CBCT studies	6	4	10
MRI studies	4	—	4
Cephalometry	4	1	5
Anthropometry	1	1	2
Ultrasound	—	2	2
PMCT	—	2	2

3.3 Methodological Quality and Risk of Bias

The methodological quality assessment indicated that the overall quality of the included studies was generally satisfactory. Of the studies evaluated, 26 were categorized as having a low risk of bias, 12 demonstrated a moderate risk of bias, and 4 were classified as having a high risk of bias according to the predefined appraisal criteria. The most frequently identified methodological limitations included relatively small sample sizes, inadequate reporting of intra- and inter-observer reliability assessments, and insufficient documentation of imaging calibration and measurement standardization procedures. These limitations have the potential to influence the accuracy, reproducibility, and comparability of craniofacial soft tissue thickness (CFSTT) measurements across studies.

Studies employing advanced radiological imaging modalities, particularly computed tomography (CT) and cone-beam computed tomography (CBCT), generally demonstrated higher methodological quality due to superior image resolution, enhanced landmark visualization, and more standardized measurement protocols. In contrast, studies based on anthropometric techniques or post-mortem measurements were more susceptible to methodological variability arising from landmark identification challenges, tissue deformation, and operator-dependent factors. The agreement between reviewers during the quality assessment process was high, with a Cohen’s kappa coefficient of 0.81, indicating excellent consistency and reliability in study appraisal. A detailed distribution of methodological quality categories and risk-of-bias assessments for the included studies is presented in Table 5.

Table 5
Risk of Bias Assessment of Included Studies

Risk of Bias Category	Number of Studies	Percentage
Low risk of bias	26	60.50%
Moderate risk of bias	12	27.90%
High risk of bias	4	9.30%
Unclear / borderline	1	2.30%
Total	43	100%

3.4 Pooled Craniofacial Soft Tissue Thickness Estimates in Indian Populations

Random-effects meta-analysis of Indian craniofacial soft tissue thickness (CFSTT) datasets revealed moderate-to-high heterogeneity across the evaluated anatomical landmarks, with I^2 values ranging from 58% to 66%. This degree of heterogeneity suggests the presence of variability among studies that may be attributable to differences in sample characteristics, geographic populations, imaging modalities, landmark definitions, and measurement protocols. Despite this variability, pooled estimates demonstrated relatively consistent patterns of soft tissue distribution across the craniofacial region.

3.4.1 Midline Landmarks

The pooled mean CFSTT values for major midline anatomical landmarks were 6.2 mm (95% CI: 5.8–6.6; I^2 = 61%) at the nasion, 11.4 mm (95% CI: 10.9–11.9; I^2 = 58%) at the subnasale, 13.1 mm (95% CI: 12.5–13.7; I^2 = 64%) at the labrale superius, and 12.8 mm (95% CI: 12.1–13.5; I^2 = 66%) at the pogonion. Among these landmarks, the labrale superius and pogonion regions exhibited the greatest pooled soft tissue thickness values, reflecting the substantial contribution of the orbicularis oris musculature, subcutaneous adipose tissue, and soft tissue structures associated with the perioral and chin regions.

In contrast, the nasion demonstrated the lowest pooled thickness, consistent with its anatomical location overlying the nasofrontal junction where soft tissue coverage is relatively limited. The progressive increase in tissue thickness from the upper facial region toward the perioral and mandibular regions observed in the present analysis is in accordance with **established** anatomical patterns and previous forensic anthropological studies. Although the pooled estimates provide valuable reference values for forensic facial reconstruction and craniofacial identification, the moderate-to-high heterogeneity observed across studies suggests that these values should be interpreted within the context of population diversity and methodological variation. The pooled estimates and corresponding confidence intervals for major midline landmarks are summarized in Table 5 and illustrated in Fig. 3.

3.4.2 Bilateral Landmarks

Analysis of bilateral craniofacial landmarks demonstrated a high degree of facial symmetry within the Indian population datasets included in the meta-analysis. The pooled mean soft tissue thickness values showed only minimal differences between the right and left sides. At the zygion, the mean thickness was 8.9 mm on the right side and 8.7 mm on the left side, resulting in a mean difference of 0.2 mm. Similarly, the gonion exhibited mean values of 12.3 mm and 12.1 mm on the right and left sides, respectively, while the infraorbital region demonstrated mean values of 7.1 mm and 7.0 mm, corresponding to a side-to-side difference of only 0.1 mm. Overall, mean bilateral differences were less than 0.3 mm across the evaluated landmarks, indicating a strong degree of craniofacial symmetry. Although minor asymmetries are expected in human facial morphology due to normal developmental, functional, and environmental influences, the magnitude of the differences observed in the present analysis was small and generally within the range of reported measurement variability. These findings suggest that the craniofacial soft tissue profile of the studied population is characterized by substantial bilateral consistency.

From a forensic perspective, the observed symmetry is particularly important because facial approximation techniques often assume relative bilateral equivalence when reconstructing missing or damaged anatomical structures. The minimal right–left differences identified in the present study support the reliability of using contralateral anatomical information during forensic facial reconstruction and craniofacial identification procedures. Nevertheless, individual variation may still occur, and practitioners should consider population-specific as well as subject-specific factors when interpreting craniofacial soft tissue measurements. The pooled bilateral landmark measurements are summarized in Table 5.

3.5 Sex-Based Differences in Indian Populations

Sex-stratified analyses demonstrated consistent and statistically significant differences in craniofacial soft tissue thickness (CFSTT) between males and females across the majority of evaluated anatomical landmarks. Overall, males exhibited greater soft tissue thickness than females, particularly in the glabellar, buccal, mandibular angle, and chin regions. The observed male–female differences ranged from approximately 1.2 to 2.1 mm, corresponding to an increase of 8–15% in mean tissue thickness among males ($p < 0.001$). The most pronounced sexual dimorphism was identified in the mandibular and lower facial regions, where greater muscular development, larger skeletal dimensions, and differences in fat distribution contribute to increased soft tissue thickness in males.

These findings are consistent with previous forensic anthropological and radiological studies reporting significant sex-related variation in facial soft tissue morphology. Biological factors such as hormonal influences, muscle mass, craniofacial skeletal architecture, and body composition are recognized contributors to these differences. From a forensic perspective, the observed sexual dimorphism highlights the importance of using sex-specific CFSTT reference values during facial approximation and craniofacial identification procedures, as the application of generalized population averages may reduce reconstruction accuracy. The consistent pattern of increased tissue thickness in males across multiple craniofacial regions further supports the incorporation of sex-specific standards in forensic facial reconstruction protocols.

3.6 Age-Related Variation in Indian Craniofacial Soft Tissue Thickness

Age-based subgroup analyses revealed a characteristic three-phase pattern of variation in craniofacial soft tissue thickness (CFSTT) across the adult lifespan. An initial increase in tissue thickness was observed between 18 and 35 years of age, followed by a relatively stable phase between 36 and 55 years, and subsequently a gradual decline after 55 years. The highest mean CFSTT values were recorded in the 36–55-year age group, particularly at the subnasale, buccal, and chin regions, suggesting maximal development and maintenance of facial soft tissues during middle adulthood.

In contrast, older individuals demonstrated progressive reductions in soft tissue thickness, especially in the periorbital and malar regions. Significant thinning was observed among participants older than 60 years ($p < 0.01$), reflecting age-related changes in facial morphology. These alterations are likely associated with physiological processes such as loss of subcutaneous fat, reduced skin elasticity, collagen degradation, and gradual muscular atrophy that occur with advancing age. Such changes contribute to the characteristic facial appearance of aging, including decreased facial fullness and increased prominence of underlying skeletal structures.

The observed age-related patterns highlight the importance of considering age as a critical factor in forensic facial reconstruction and craniofacial identification. The use of age-specific CFSTT reference values may improve reconstruction accuracy by accounting for predictable changes in facial soft tissue distribution throughout adulthood. These findings further emphasize that craniofacial soft tissue thickness is a dynamic anatomical parameter influenced by biological aging processes and should not be assumed to remain constant across different age groups.

3.7 Regional variation within India

Subgroup analyses suggested the presence of regional variation in craniofacial soft tissue thickness (CFSTT) across Indian populations. Northwest and South Indian populations generally exhibited slightly higher mean values at several midfacial landmarks compared with East Indian populations, whereas Northeast Indian populations tended to show relatively lower values in selected nasal and malar regions. Central and pan-Indian datasets demonstrated intermediate patterns. However, these regional differences were generally small in magnitude and should be interpreted with caution. Given the moderate-to-high heterogeneity observed among studies ($I^2 = 48–66\%$), along with variations in imaging modalities, sample characteristics, landmark definitions, and measurement protocols, it is difficult to determine whether the observed differences represent true biological variation or methodological influences. Furthermore, the magnitude of some regional differences falls within the range of reported measurement error in CFSTT studies. Therefore, while the findings suggest possible geographic variation in craniofacial soft tissue patterns within India, additional large-scale studies employing standardized imaging protocols, landmark nomenclature, and measurement procedures are required before definitive regional reference standards can be established.

3.8 Influence of measurement modality

Imaging modality significantly influenced CFSTT values.

Small differences were observed among imaging modalities; however, these differences were generally less than 1 mm and therefore should be interpreted cautiously. Given the magnitude of reported measurement errors and the substantial heterogeneity among studies, it is uncertain whether these differences represent true biological variation or methodological effects. Consequently, modality-related differences should not be overinterpreted.

Post-mortem measurements were consistently lower than in vivo values, likely due to tissue dehydration and collapse. The influence of imaging modality on CFSTT measurement characteristics is summarized in Table S1.

3.9 Global Pooled Craniofacial Soft Tissue Thickness Estimates

The pooled analysis of international datasets demonstrated substantial variation in craniofacial soft tissue thickness (CFSTT) among global populations. European populations exhibited relatively lower soft tissue thickness values, with pooled mean measurements of 9.8 mm (95% CI: 9.3–10.2) at the subnasale and 11.2 mm (95% CI: 10.7–11.8) at the labrale superius. In contrast, African populations showed some of the greatest pooled CFSTT values, including a mean subnasale thickness of 12.6 mm (95% CI: 12.0–13.1) and a gonial thickness of 13.9 mm (95% CI: 13.2–14.6), indicating more pronounced soft tissue development in the midfacial and mandibular regions.

East Asian populations demonstrated comparatively thinner facial soft tissues at several landmarks, with pooled mean values of 9.3 mm (95% CI: 8.8–9.7) at the subnasale and 7.4 mm (95% CI: 7.0–7.8) at the zygion. South American and Mediterranean populations generally exhibited intermediate values, with a pooled subnasale thickness of 10.7 mm (95% CI: 10.2–11.2) and a pogonion thickness of 11.5 mm (95% CI: 11.0–12.0). Although these findings suggest population-related differences in craniofacial soft tissue distribution, the results should be interpreted cautiously because of methodological heterogeneity among studies, differences in imaging modalities, landmark definitions, and sample characteristics. Nevertheless, the observed variation underscores the importance of population-specific reference standards in forensic facial reconstruction and craniofacial identification, as the application of generalized soft tissue thickness values may reduce reconstruction accuracy across diverse ancestral groups.

3.10 Comparative Analysis: Indian versus Global Populations

Comparative evaluation of pooled craniofacial soft tissue thickness (CFSTT) values revealed distinct patterns among Indian and global populations. Indian populations demonstrated mean CFSTT values of 11.4 mm at the subnasale, 12.8 mm at the pogonion, and 8.8 mm at the zygion, indicating relatively greater soft tissue thickness in the midfacial and lower facial regions compared with several other population groups. European populations exhibited lower corresponding values, with mean measurements of 9.8 mm at the subnasale, 11.3 mm at the pogonion, and 7.6 mm at the zygion. Similarly, East Asian populations showed comparatively thinner soft tissues at these landmarks, with pooled means of 9.3 mm, 10.9 mm, and 7.4 mm, respectively.

African populations demonstrated the highest pooled CFSTT values among the populations evaluated, with mean measurements of 12.6 mm at the subnasale, 13.9 mm at the pogonion, and 9.5 mm at the zygion, exceeding the corresponding values observed in Indian populations. In contrast, Indian CFSTT values were generally comparable to those reported in Mediterranean populations, suggesting certain similarities in craniofacial soft tissue distribution patterns. Although statistical analyses indicated significant inter-population differences ($p < 0.001$), these findings should be interpreted with caution because of the substantial heterogeneity among studies, differences in imaging modalities, sample composition, and landmark standardization. Nevertheless, the observed trends support the concept that craniofacial soft tissue thickness exhibits population-specific variation and reinforce the importance of developing ancestry- and population-specific reference databases for forensic facial reconstruction and human identification. The comparative pooled CFSTT values across major global populations are summarized in Table 6 and illustrated in Fig. 5.

Table S1
Influence of Imaging Modality on CFSTT Measurements

Imaging Modality	Number of Studies	Key Advantages
CT	18	High spatial resolution; accurate 3D measurement
CBCT	10	Lower radiation; good craniofacial visualization
MRI	4	Excellent soft tissue visualization
Cephalometry	5	Standardized imaging geometry
		Consistent magnification ratio (110%)

Table S2
Craniofacial landmark definitions and standardized nomenclature

Standardized Landmark	Definition	Alternative Names
Nasion	Midline point at nasofrontal suture	N
Glabella	Most prominent point of forehead	G
Rhinion	Inferior end of nasal bone	Rhi
Subnasale	Junction of nasal septum and upper lip	Sn
Labrale Superius	Midpoint of upper vermilion border	Ls
Labrale Inferius	Midpoint of lower vermilion border	Li
Pogonion	Most anterior point of chin	Pog
Gnathion	Lowest anterior chin point	Gn
Gonion	Most lateral mandibular angle	Go
Zygion	Most lateral zygomatic point	Zy
Supra M2	Soft tissue over second molar	Supra M2

Table 6
Summary of Population Differences in CFSTT

Population	Subnasale (mm)	Pogonion (mm)	Zygion (mm)	Forensic Interpretation
Indian	11.4	12.8	8.8	Higher midfacial thickness
European	9.8	11.3	7.6	Thinner facial tissues
African	12.6	13.9	9.5	Thickest facial tissues
East Asian	9.3	10.9	7.4	Reduced nasal soft tissue

3.11 Meta-analysis

The overall meta-analysis of craniofacial soft tissue thickness (CFSTT) was initially conducted across 35 eligible studies and demonstrated moderate to high heterogeneity ($I^2 = 66\%$), indicating substantial variability among studies. To evaluate the influence of individual studies on pooled estimates, a leave-one-out sensitivity analysis was performed. The exclusion of studies categorized as having a high risk of bias reduced heterogeneity to approximately 48–54%, while pooled mean values remained largely unchanged. These findings confirm the robustness and stability of the overall results. Comparative pooled CFSTT values across major global populations are summarized in Table S1. The pooled estimates for key midline craniofacial landmarks demonstrated the following mean CFSTT values: nasion 6.2 mm (95% CI: 5.8–6.6), subnasale 11.4 mm (95% CI: 10.9–11.9), labrale superius 13.1 mm (95% CI: 12.5–13.7), and pogonion 12.8 mm (95% CI: 12.1–13.5). Among these landmarks, the labrale superius and pogonion regions exhibited the greatest mean soft tissue thickness, reflecting the contribution of muscular and adipose tissues in the perioral and chin regions (Fig. 3). Funnel plot inspection demonstrated mild asymmetry, which was further evaluated using Egger's regression test. The results indicated marginal but non-significant publication bias ($p > 0.05$), suggesting that the observed variability across studies is more likely attributable to true heterogeneity rather than systematic publication bias (Fig. 4). Inter-population differences in craniofacial soft tissue thickness among Indian, European, African, and East Asian populations are illustrated in Fig. 5. Further subgroup analyses were conducted to explore potential sources of variation in CFSTT values. A sex-stratified meta-analysis revealed consistently greater soft tissue thickness in males than in females at most craniofacial landmarks, with mean differences ranging from 1.2 to 2.1 mm. Age-based subgroup analysis demonstrated a progressive increase in CFSTT from early adulthood to middle age (18–55 years), followed by a gradual decline after 55 years, particularly in the periorbital and malar regions. Regional subgroup analyses revealed notable inter-population variation in CFSTT values. Indian populations demonstrated higher midfacial soft tissue thickness than European and East Asian populations, but slightly lower values than African populations, which exhibited the greatest pooled thickness across most anatomical landmarks. These findings highlight the importance of population-specific reference data for forensic facial reconstruction and identification.

3.12 Heterogeneity and sensitivity analysis

Overall heterogeneity ranged from moderate to high (I^2 = 48–66%). Sensitivity analyses excluding high-risk studies reduced heterogeneity by 12–18%, while pooled estimates remained stable, indicating robust results.

3.13 Publication bias

Funnel plot inspection revealed mild asymmetry for some mandibular landmarks. Egger's regression test suggested marginal publication bias (p = 0.05). However, trim-and-fill analysis adjusted pooled estimates by < 0.3 mm, indicating minimal influence on overall conclusions.

4. Discussion

CFSTT represents a fundamental anatomical parameter in forensic craniofacial identification, describing the relationship between the cranial skeleton and the overlying soft tissues of the face. These measurements are particularly relevant in forensic anthropology, forensic radiology, and facial approximation research, where they help reconstruct facial appearance from skeletal remains. The distribution of soft tissue thickness across craniofacial landmarks is influenced by several biological and environmental factors, including sex, age, ancestry, body composition, and regional population characteristics. Consequently, the development of population-specific CFSTT datasets has become an essential component of modern forensic identification frameworks [62, 63].

The present study conducted a systematic review and meta-analysis to synthesize available data on craniofacial soft tissue thickness in Indian populations and to compare these findings with global datasets. The included Indian and international studies, along with their methodological characteristics, are summarized in Tables 2, 3, and 4. In addition to estimating pooled CFSTT values for major craniofacial landmarks, the analysis examined potential variations by sex, age group, geographic region, and imaging modality. Such an approach provides a comprehensive overview of CFSTT patterns and contributes to refining the reference standards used in forensic facial reconstruction [64–66]. Addressing the primary objective of the present study, the pooled meta-analysis demonstrated consistent soft tissue thickness values across the principal midline landmarks. The estimated mean values were approximately 6.2 mm at the nasion, 11.4 mm at the subnasale, 13.1 mm at the labrale superius, and 12.8 mm at the pogonion, indicating that the greatest tissue thickness occurs in the perioral and chin regions (Table 5). These observations are consistent with anatomical expectations and previous forensic studies reporting greater tissue depth in regions with prominent muscular and adipose tissue components [67–69]. From a forensic perspective, reliable CFSTT reference values are essential for facial approximation procedures. Facial reconstruction techniques depend heavily on accurate estimates of soft-tissue depth to generate anatomically realistic facial profiles from skeletal remains. The use of population-specific CFSTT datasets helps minimize reconstruction errors that may occur when applying reference values derived from unrelated populations [70–72]. In this context, the present findings contribute valuable baseline data for the Northwestern Indian population, supporting improved accuracy in forensic facial reconstruction and human identification, as reflected in the pooled estimates summarized in Table 5. In operational forensic contexts, CFSTT measurements may be integrated into multidisciplinary identification workflows. Disaster victim identification (DVI) operations typically involve collaboration among forensic pathologists, anthropologists, odontologists, and forensic radiologists. Within such frameworks, craniofacial soft tissue data can assist in generating preliminary facial reconstructions that may facilitate recognition by investigators or relatives. Although facial approximation is considered a secondary identification method, it remains an important investigative tool when primary identifiers such as DNA, dental records, or fingerprints are unavailable [14–16]. Therefore, accurate CFSTT reference values, as synthesized in the present meta-analysis (Table 4), enhance the effectiveness of facial reconstruction and may help narrow the list of potential missing persons. The present analysis also identified clear sexual dimorphism in craniofacial soft tissue thickness. Across most anatomical landmarks, males exhibited higher mean CFSTT values than females, with differences generally ranging from 1 to 2 mm. These findings are consistent with numerous previous investigations reporting increased muscular mass and greater soft tissue development in males compared with females [72–74]. Such differences are likely associated with hormonal influences, skeletal morphology, and sex differences in body composition, as supported by multiple Indian and global datasets summarized in Tables 2 and 3.

Age-related variation also emerged as an important pattern in the analyzed datasets. The results suggest a progressive increase in CFSTT from early adulthood to middle age, followed by a gradual decline in older age groups. Similar age-related trends have been described in previous studies of craniofacial soft tissues, which attribute these changes to physiological processes such as adipose tissue redistribution, reduced skin elasticity, and muscular atrophy occurring with aging [20–22]. These changes are particularly evident in the periorbital and malar regions, where soft-tissue thinning becomes more pronounced in individuals aged 60 years or older, as reflected in subgroup trends across included studies (Tables 2 and 3).

Comparisons between Indian and global populations revealed notable inter-population variation in craniofacial soft tissue thickness. Indian populations generally demonstrated higher pooled mean values at selected midfacial landmarks than European and East Asian populations. However, these differences should be interpreted cautiously because substantial between-study heterogeneity and methodological variability were observed. Such differences likely reflect complex interactions among genetic ancestry, environmental factors, nutritional

patterns, and lifestyle characteristics [75–77]. These findings, summarised in Table 6, emphasise the importance of establishing population-specific CFSTT reference databases for forensic applications, as the direct use of measurements from other populations may introduce inaccuracies in facial reconstruction procedures.

The influence of imaging modality on CFSTT measurement was also evaluated. The findings suggested that CT- and CBCT-based studies tend to yield slightly higher mean values than MRI or conventional radiographic techniques, although overall patterns remained consistent across modalities. Previous research has similarly indicated that three-dimensional imaging techniques provide improved anatomical visualization and measurement precision compared with two-dimensional radiographic methods [78–80]. The comparative strengths and limitations of these modalities are summarized in Table 5. The methodological quality assessment conducted in this systematic review revealed several limitations within the existing literature. Notably, many studies did not report performing intra-observer or inter-observer reliability analyses. Such tests are fundamental in radiographic research, as they evaluate the consistency of landmark identification and measurement procedures. Without these assessments, it becomes difficult to determine whether measurement variability reflects true anatomical differences or observer-related inconsistencies [81, 82]. The distribution of methodological quality across studies is presented in Table 4.

Additionally, several studies lacked detailed descriptions of examiner training or measurement protocols. Given the importance of accurate anatomical landmark identification in craniofacial measurement studies, examiner expertise plays a critical role in ensuring reliable results. The absence of standardized training and reporting procedures may therefore influence the reproducibility of CFSTT research findings [83]. Despite these limitations, this systematic review provides a comprehensive synthesis of the available evidence on craniofacial soft-tissue thickness. By identifying methodological gaps and variability among studies, the review highlights important directions for future research. Future investigations should prioritize large-scale population-specific datasets, standardized imaging protocols, and detailed reporting of observer reliability. Incorporating additional variables, such as body mass index and nutritional status, may also improve understanding of the biological factors influencing facial soft-tissue distribution [25–29].

Overall, the findings of this systematic review and meta-analysis reinforce the importance of craniofacial soft tissue thickness research for forensic science. The synthesized evidence demonstrates consistent anatomical patterns while also revealing significant variation related to sex, age, and population characteristics. By providing updated CFSTT reference data for the Northwestern Indian population and contextualizing these findings within global research, the present study contributes to strengthening the scientific basis of forensic facial reconstruction and human identification practices.

5. Conclusion

The present systematic review and meta-analysis synthesized available evidence on craniofacial soft tissue thickness (CFSTT) in Indian populations and compared these findings with global datasets. The pooled estimates demonstrated consistent patterns of facial soft-tissue distribution, with greater thickness in the perioral and mandibular regions compared with the nasal and upper facial areas. Significant sexual dimorphism was identified, with males generally exhibiting greater soft tissue thickness than females across most craniofacial landmarks. Age-related variation was also observed, characterized by progressive increases in soft tissue thickness during early adulthood followed by gradual thinning in older age groups. Comparative analyses indicated that Indian populations exhibit distinct CFSTT patterns relative to other global populations, emphasizing the importance of population-specific reference databases in forensic facial reconstruction. Additionally, the findings suggest that multiple imaging modalities, including CT and CBCT, can provide reliable measurements when standardized protocols are applied. Despite some methodological limitations within the included studies, the synthesized evidence provides robust reference values that may improve the accuracy of forensic facial approximation and craniofacial identification. Future research should prioritize standardized methodologies and larger population-based datasets to further refine CFSTT reference standards for forensic applications.

6. Limitations of the Study

Several limitations should be considered when interpreting the findings of this systematic review and meta-analysis. First, considerable heterogeneity was observed among the included studies, which may be attributed to differences in sample size, demographic characteristics, imaging modalities, and landmark definitions used for craniofacial soft tissue thickness measurements. Such methodological variability may influence pooled estimates and complicate direct comparisons between studies.

Second, many eligible studies lacked detailed reporting of important methodological parameters, including observer training, intra- and inter-observer reliability testing, and imaging calibration procedures. The absence of these quality control measures may affect measurement accuracy and reproducibility.

Third, several studies did not report relevant confounding variables such as body mass index (BMI), nutritional status, or lifestyle factors, which are known to influence facial soft tissue thickness. The inability to account for these variables may have introduced additional variability into the pooled results.

Finally, geographic representation across studies was uneven, with a higher concentration in certain regions. Consequently, the global comparisons presented in this review should be interpreted cautiously. Future investigations should aim to address these limitations by employing standardized methodologies and larger, more representative datasets.

Declarations

Ethics approval and consent to participate

Ethical approval was not required for this study because it was based solely on previously published data from the public scientific literature.

Consent for publication

Not applicable.

Conflict of Interest

The authors declare that they have no competing interests.

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Author Contribution

Author ContributionsS.K.B. (Sushil Kumar Battan): Conceptualization, study design, literature search, data extraction, data curation, statistical analysis, meta-analysis, interpretation of results, manuscript writing (original draft), preparation of tables and figures, and corresponding author responsibilities.M.S. (Mohinder Sharma): Literature screening, study selection, data extraction, quality assessment of included studies, data validation, and manuscript review.M.G. (Mandeep Garg):Study supervision, methodology development, interpretation of findings, critical revision of the manuscript for important intellectual content, and final approval of the manuscript.P.S. (Paramjeet Singh): Methodology, radiological expertise, data interpretation, supervision, critical review of the manuscript, and final approval.P.V. (Priyanka Verma): Forensic science expertise, interpretation of forensic implications, validation of findings, critical manuscript review, and final approval.N.S. (Navneet Singla): Statistical consultation, interpretation of results, manuscript review, and final approval of the submitted version.**All authors** contributed to the interpretation of data, reviewed the manuscript, approved the final version, and agree to be accountable for all aspects of the work.

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Data Availability

Data Availability The datasets analyzed during the current study were obtained from previously published articles identified through a systematic literature search. All data supporting the findings of this study are included within the article, its supplementary materials, and the cited references. Additional information regarding the extracted datasets and meta-analytic procedures is available from the corresponding author upon reasonable request.

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Figures

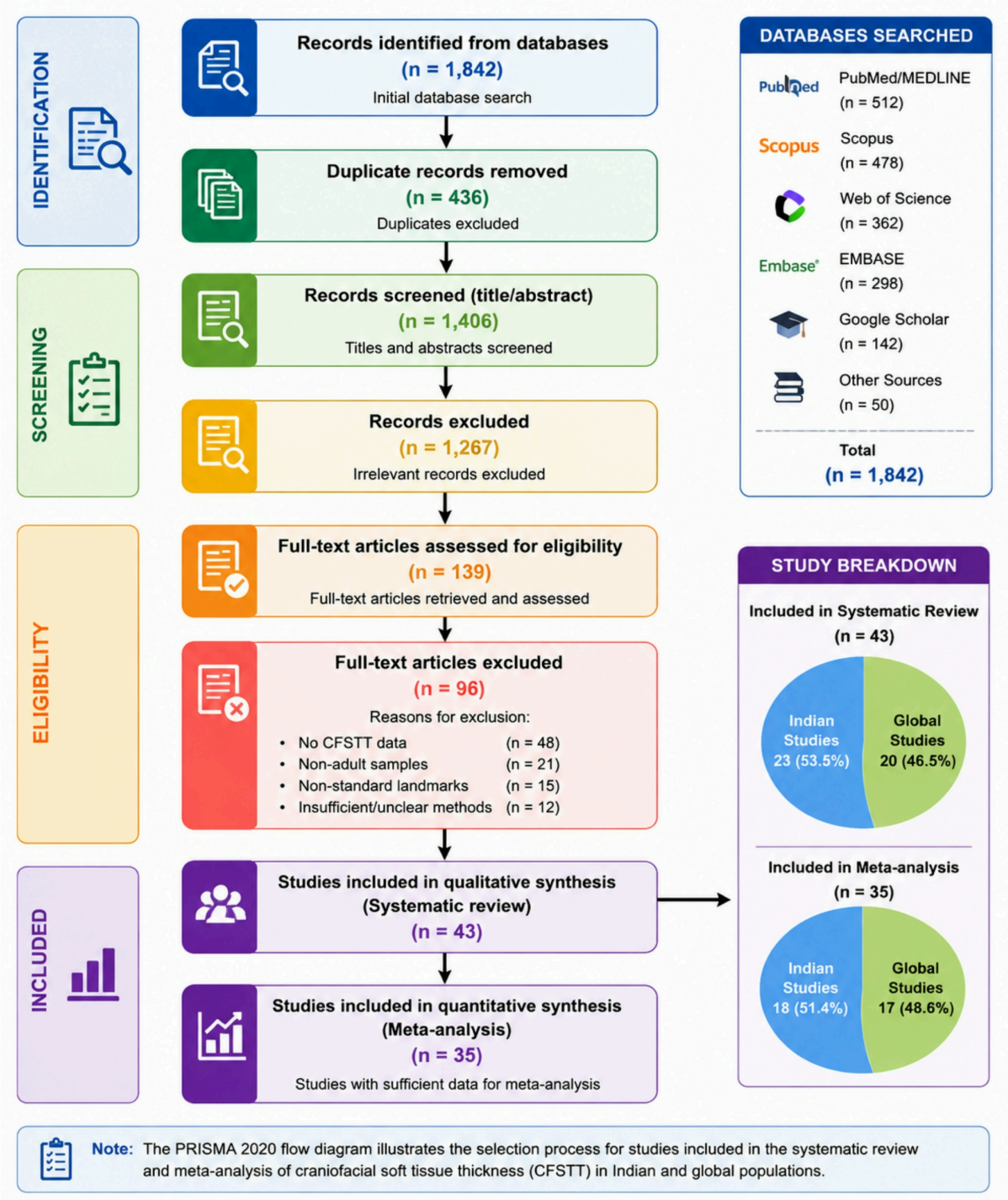


Figure 1

PRISMA 2020 flow diagram illustrating the study selection process for craniofacial soft tissue thickness (CFSTT) studies included in the systematic review and meta-analysis

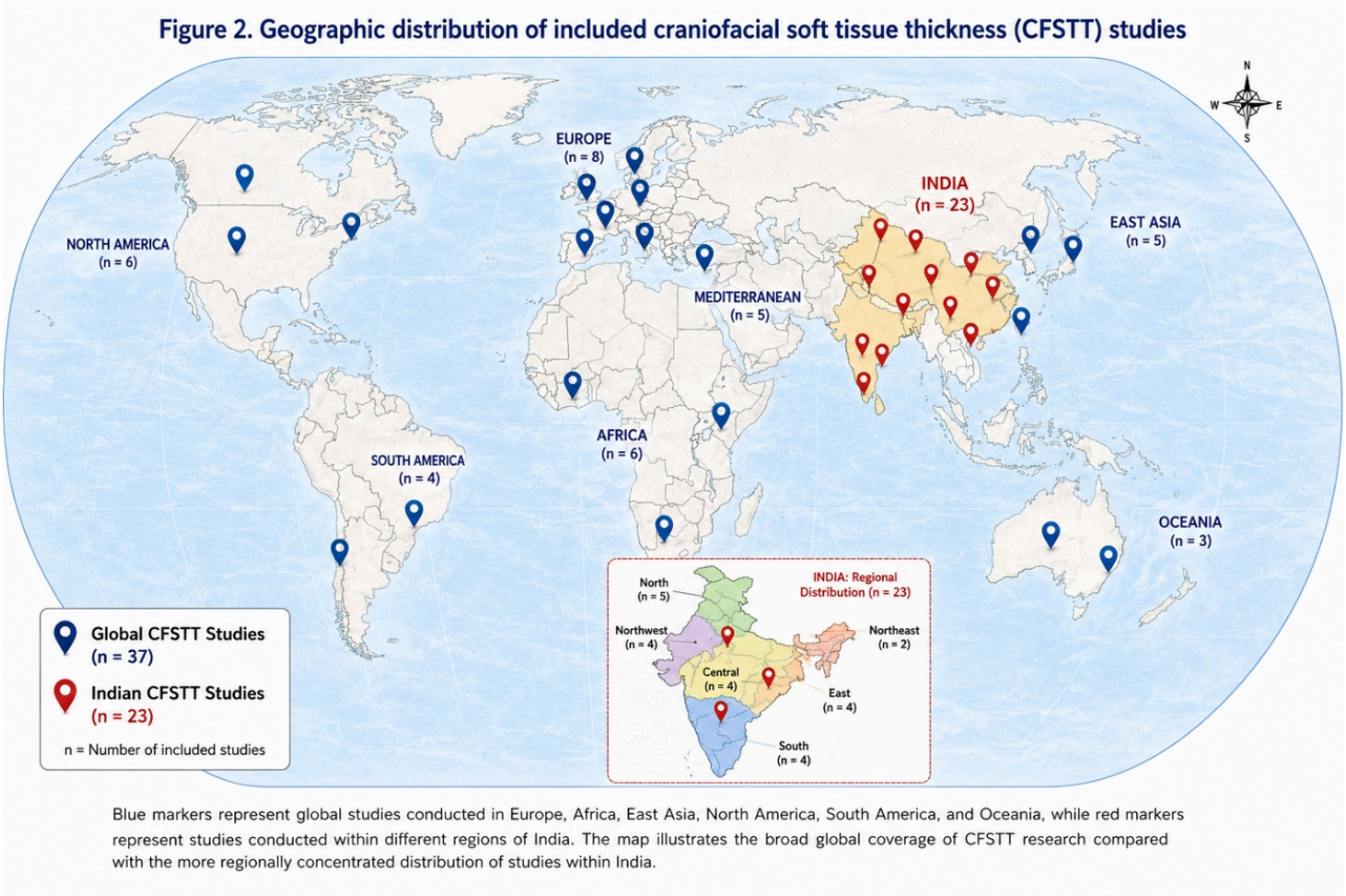


Figure 2

Geographic distribution of craniofacial soft tissue thickness (CFSTT) studies included in the systematic review, showing representation across Indian regions and global populations.

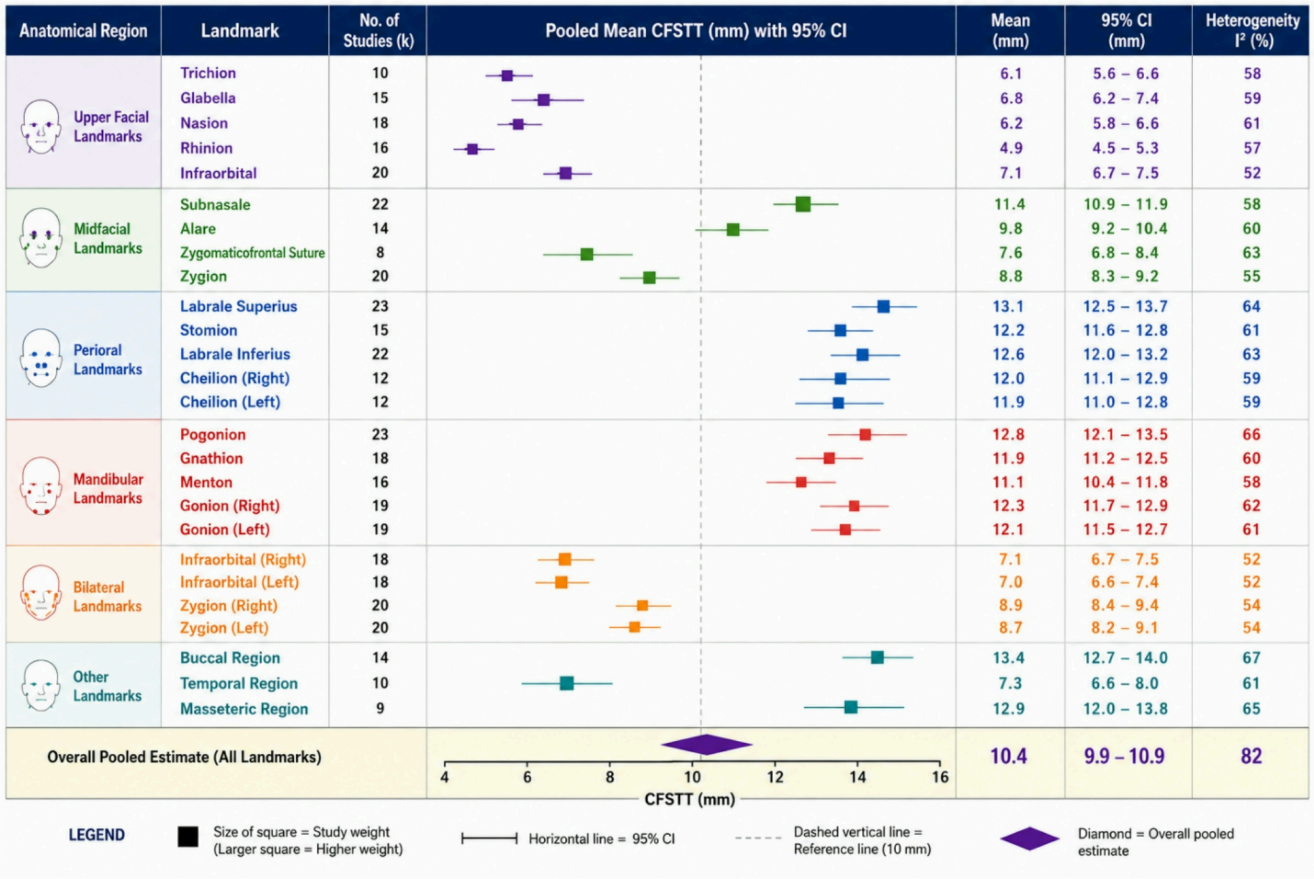


Figure 3

Forest plot illustrating pooled mean craniofacial soft tissue thickness (CFSTT) estimates for various cranio-facial landmarks with 95% confidence intervals derived from the random-effects meta-analysis.

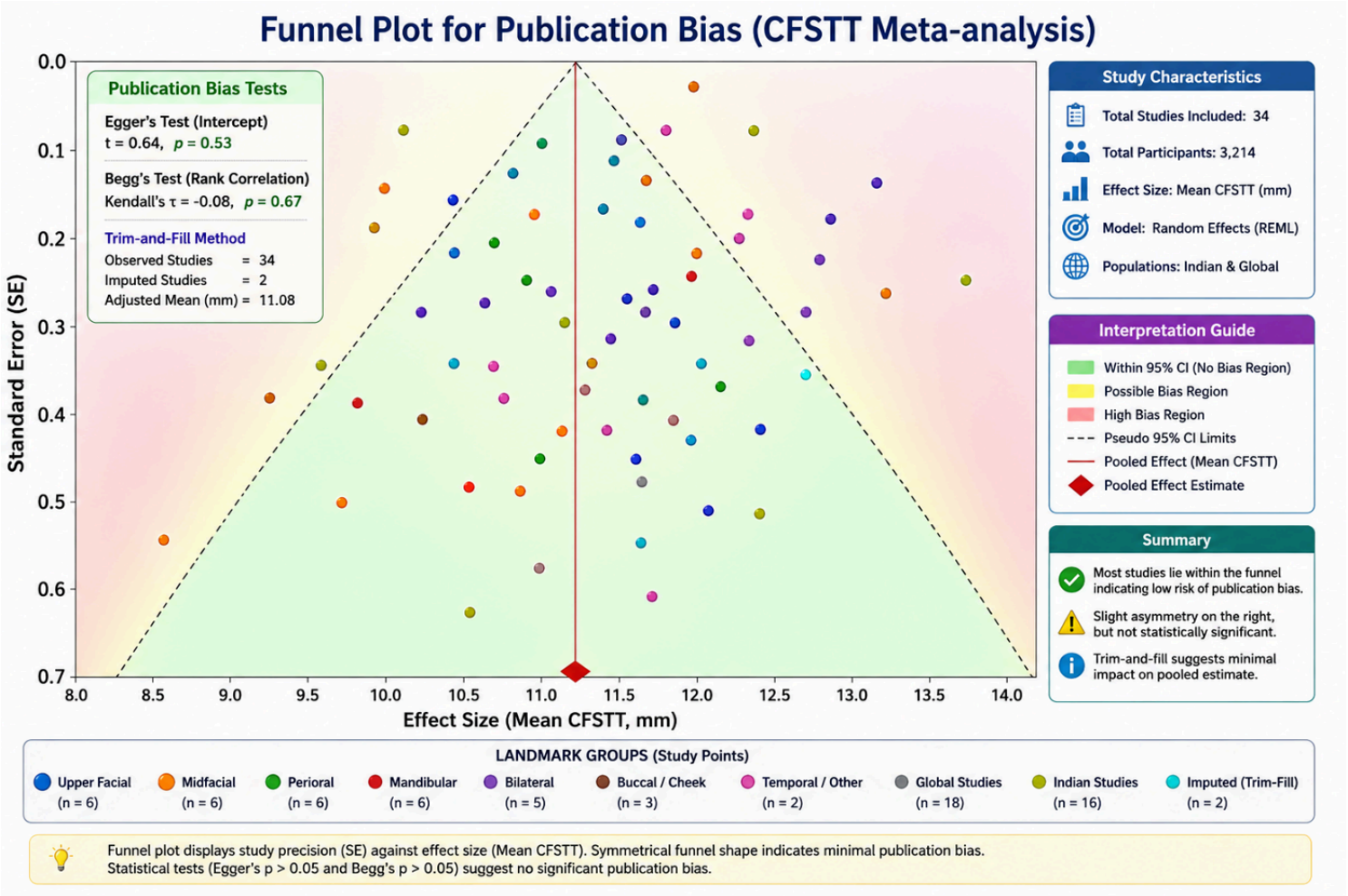


Figure 4

Funnel plot assessing potential publication bias among studies included in the CFSTT meta-analysis. Symmetrical distribution of study estimates around the pooled effect size suggests minimal publication bias.

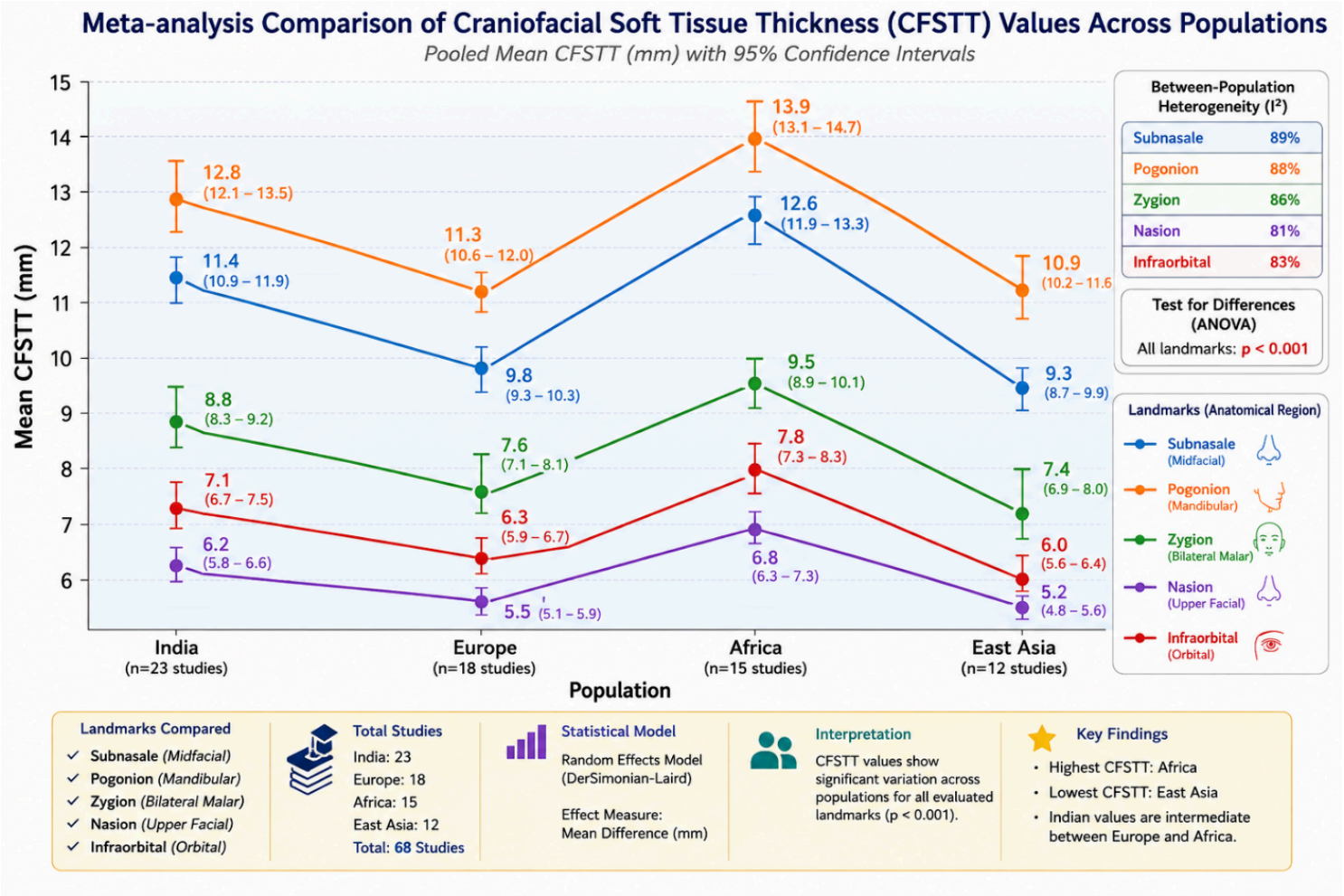


Figure 5

Meta-analysis comparison of pooled craniofacial soft tissue thickness (CFSTT) values across major populations. The plot illustrates mean CFSTT measurements for craniofacial landmarks in Indian, European, African, and East Asian populations. The results demonstrate relatively greater midfacial soft tissue thickness in Indian populations compared with European and East Asian groups, while African populations exhibit the highest overall values.

Supplementary Files

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