

ORIGINAL ARTICLE

Biologically Anchored AI Analysis of Craniofacial Traits for Cyber and Digital Forensics: A Multigenerational Indian Study

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ABSTRACT

Background: Facial biometrics play a critical role in cybercrime investigations, digital identity verification, and surveillance-based forensic systems. Despite their widespread use, many artificial intelligence (AI)-driven facial recognition pipelines operate without biologically validated craniofacial feature foundations, raising concerns regarding interpretability, bias, and forensic reliability.

Aim: This study aims to establish a biologically grounded framework for AI-assisted forensic facial analysis by examining the inheritance, stability, and predictability of live craniofacial anthropometric traits across three biological generations of Indian families.

Methods: A total of 216 individuals from 48 Indian families spanning three generations were examined. Fourteen standardized craniofacial dimensions were recorded using calibrated vernier callipers under natural head position. Trait normalization, intergenerational comparisons, heritability estimation, transfer score analysis, and machine-learning-based predictability assessment were performed using robust statistical modeling and AI-assisted analytical techniques.

Result: Craniofacial traits exhibited uneven hereditary patterns. Vertical craniofacial dimensions demonstrated greater generational resemblance, biological stability, and algorithmic predictability compared to horizontal traits. Sto-Sl, En-Ex, and Zy-Zy emerged as highly stable and forensically reliable craniofacial features with strong heritability and predictive performance.

Conclusion: The study provides a statistically validated and biologically explainable reference framework for AI-based facial analysis in cyber and digital forensic applications. By anchoring AI models to biologically stable craniofacial traits, the findings enhance the reliability, interpretability, and forensic admissibility of facial evidence.

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KEYWORDS

• Craniofacial anthropometry • Facial biometrics • Artificial intelligence • Digital forensics • Cybercrime • Forensic identification • Heritability

INTRODUCTION

Facial biometrics are now part of the contemporary cyber and digital forensic systems, applications of identity verification, criminal investigation, border security, surveillance analytics, and cybersecurity authentication are part of its applications. Facial recognition systems are becoming increasingly relied upon by law enforcement agencies to identify their suspected offenders through surveillance videos, social media photos, and electronic devices recovered during an actual case. Nevertheless, the majority of the frameworks based on artificial intelligence (AI) to produce facial recognition output are created in the form of computational models without a direct reference to the biological set-up of the human face.

Craniofacial morphology is a very complex biological system that is controlled by genetic inheritance, developmental biology and biomechanical integration. The use of craniofacial measures in human identification, the determination of ancestry, and the reconstruction of kinship has been used for a long time in forensic anthropology.¹⁻⁶ These are not arbitrary geometric properties but biologically constrained dimensions that have been determined by the structures that we have inherited skeletons and are altered by the effects created by the environment.⁷⁻⁹

Modern digital forensics investigations are mainly based on 2D facial images taken under uncontrolled conditions, that is, CCTV video, cell phone pictures, and social media materials.¹⁰⁻¹² Facial recognition systems based on AI are able to extract landmarks and facial embeddings of such images, and by default, all facial features are treated equally. This supposition is not consistent with anthropometric data as craniofacial characteristics vary significantly in the biological stability, strength of heredity and reliability of measurements.^{1,2,13,14}

Unless AI-derived facial features are based on biologically validated craniofacial features, digital forensic systems are prone to algorithmic prejudice, diminished interpretability, and law.

There is an increasing demand in the courts to demand transparency in biometric evidence, its explainability, and scientific validation.¹⁵⁻¹⁷ Thus, the use of artificial intelligence and forensic anthropology will be a necessity in ensuring the reliability, admissibility, and credibility of digital facial evidence.

This is a critical gap that the current research will address through a systematic investigation of live craniofacial anthropometric traits of three generations of biological generations of Indian families employing the use of robust statistical modelling and AI-assisted analysis. The goal provides a framework of biological ground truth upon which later photographic and machine-learning analyses may be established and a valid anthropometric basis to cyber and digital forensic facial biometrics.

This study aims to establish a biologically grounded framework for AI-assisted forensic facial analysis by examining the inheritance, stability, and predictability of live craniofacial anthropometric traits across three biological generations of Indian families. Our objectives include:

- To analyze craniofacial trait inheritance across three generations.
- To identify stable and heritable craniofacial features.
- To assess the predictive suitability of these traits using AI models.

MATERIALS AND METHODS

This cross-sectional family-based study included 216 individuals from 48 Indian families, spanning three biological generations (Table 1) i.e. Generation 1 (Grand-parents), Generation 2 (Parents) and Generation 3 (Children).^{1,3,5,18} Participants were aged 12-65 years,^{1,6,21,22} with no history of congenital facial anomalies, trauma, or reconstructive surgeries.^{10,23} Craniofacial measurements were taken using calibrated vernier calipers in Natural Head Position (NHP) to ensure accuracy.^{5,14,21,23,24}

Table 1: Distribution of participants across three biological generations.

Generation		
Gen1 (Grandparents)		
Gen2 (Parents)		
Gen3 (Children)		

Fourteen standardized craniofacial dimensions (Table 2) were measured, including both horizontal (e.g., En-En, Zy-Zy) and vertical dimensions (e.g., N-Gn, Sn-Gn).^{1,2,22} Each measurement was repeated three times, and the average was used for analysis to minimize intra-observer error.⁵ Data analysis

involved statistical techniques such as Yeo-Johnson or Box-Cox transformations, ANOVA, Kruskal-Wallis²⁵ and machine learning regression models to assess heritability, generational similarity, and predictive power of craniofacial traits.²⁶⁻²⁸

Table 2: Description of fourteen standardized craniofacial landmarks used in the study

Measurement Type	Landmark	Definition
Horizontal Measurements	Go-Go (Gonion)	The linear distance between the outermost points of the jawbone, defined as the gonion (Go) bilaterally.
	Al-Al (Nose Width)	The linear distance between the alare points (Al), which represent the outermost points of the nostrils.
	Ex-Ex (Outer eye corners)	The linear distance between the outer corners of the eyes, known as the exocanthions (Ex).
	En-En (Inner Eye corners)	The linear distance between the inner corners of the eyes, known as the endocanthions (En).
	Zy-Zy (Cheekbone width)	The linear distance between the zygion points (Zy), which correspond to the widest points of the cheekbones.
	Ch-Ch (Mouth width)	The linear distance between the chelion points (Ch), representing the outermost corners of the mouth.
	En-Ex (Eye Fissure length)	The horizontal width of a single eye opening.
Vertical Measurements	N-Gn (Nasion - Gnathion)	The linear distance from the nasion (N), located at the root of the nose between the eyebrows, to the gnathion (Gn), the lowest point of the chin.
	N-Sn (Nose height)	The linear distance from the nasion (N) to the subnasale (Sn), located at the junction of the columella and the upper lip.
	Sto-Gn (Stomion - Gnathion)	The linear distance from the stomion (Sto), the midpoint of the oral fissure, to the gnathion (Gn).
	Sn-Sto (Subnasale - Stomion)	The linear distance from the subnasale (Sn) to the stomion (Sto).
	N-Sto (Nasion -Stomion)	The linear distance from the nasion (N) to the stomion (Sto).
	Sn-Gn ((Subnasale -Gnathion)	The linear distance from the subnasale (Sn) to the gnathion (Gn).
	Sto-Sl (Stomion - Sublabiale)	The linear distance from the stomion (Sto) to the soft tissue menton (Sl), representing the most anterior point of the chin in the midline.

RESULTS

Trait-wise distributional evaluation gave significant differences in dimensions craniofacial. Characteristics like the En-Ex, Sn-Sto, Sto-Gn, Sto-Sl and Zy-Zy had significant deviation in the normativity in the raw form, and this was indicative of inherent biological and developmental variability.

The post-transformation diagnostics verified that the alignment with the parametric

assumptions was enhanced that the inference made at the next stage incorporated biological variation and not statistical artefacts.²⁵

Comparison at generation levels found only three characteristics (Al-Al, Ch-Ch, Sn-Sto) that formed statistically significant differences between generations as shown in the Manhattan-plot (Figure 1). Most of the craniofacial traits were fixed, which means that there were high levels of structural conservation among the lineages (Figure 1).

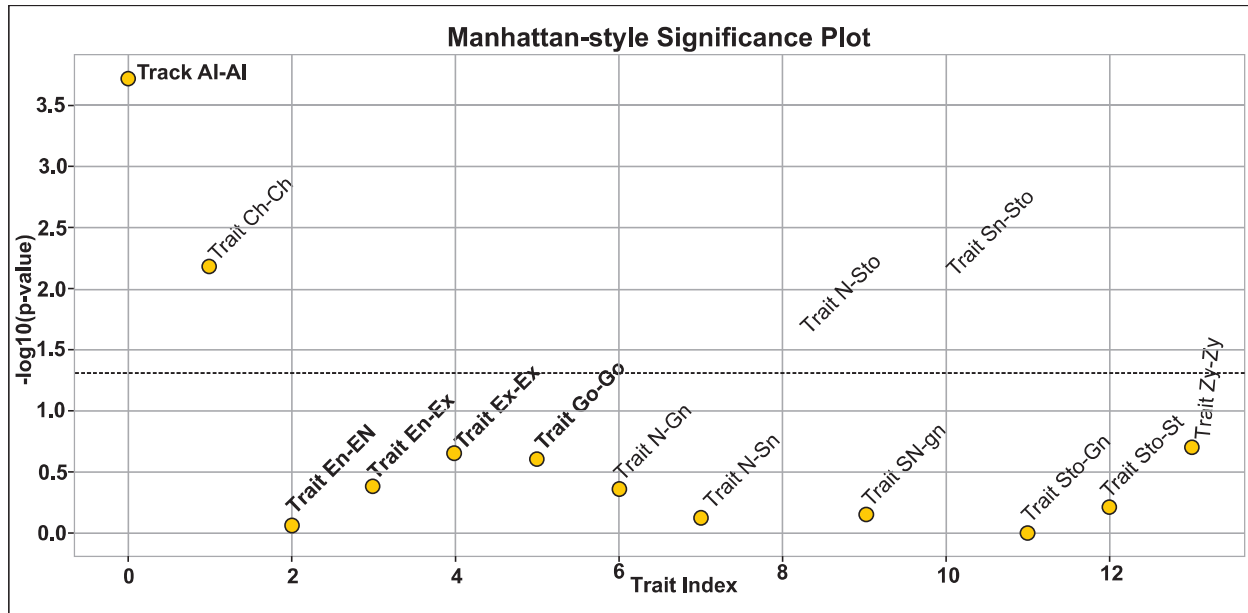


Figure 1: Trait-wise Manhattan-style significance plot showing generational differences in craniofacial dimensions

This small generational deviation is an argument in favour of the biological stability of craniofacial morphology and confirms its comparison to the modelling of inheritance.^{1,2,5}

The estimate of heritability showed uneven heritability of craniofacial dimensions. En-Ex, Sto-SI and Zy-Zy exhibited high heritability, especially Gen2 -Gen3 and Gen1 -Gen3 (Figure 2).

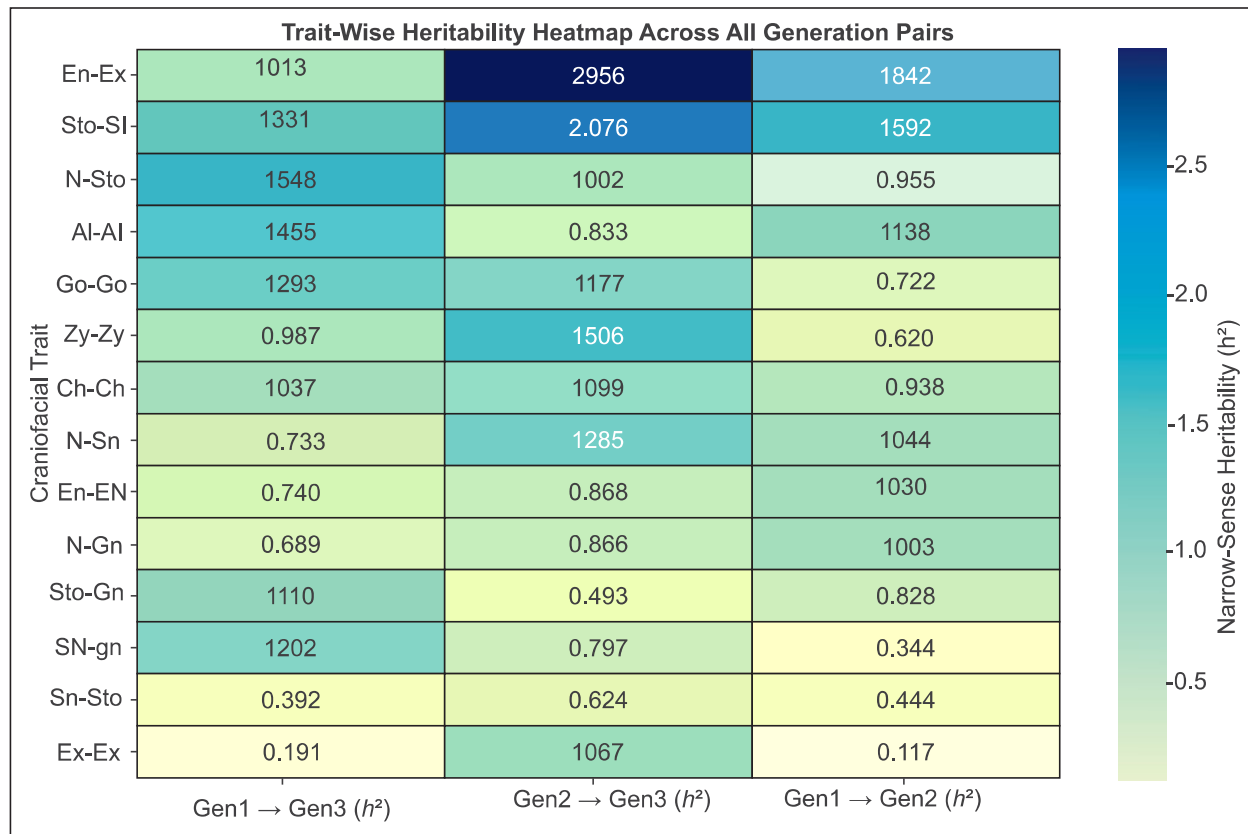


Figure 2: Trait-wise heritability (h^2) heatmap across all generation pairs (Gen1→Gen2, Gen2→Gen3, Gen1→Gen3)

N-Sn, Ch-Ch, En-En, Al-Al, and Go-Go had moderate heritability and all the others (Ex-Ex, Sn-Sto, Sto-Gn, etc.) had low heritability (Figure 2).

These results support earlier craniofacial studies on inheritance evidence that indicates a trait genetic contribution.^{1-4,6}

Vertical craniofacial measures (mean transfer score 0.389) showed more similarity than horizontal characteristics (mean transfer score 0.336) and were more signs of greater generational similarity and biological stability (Figure 3).

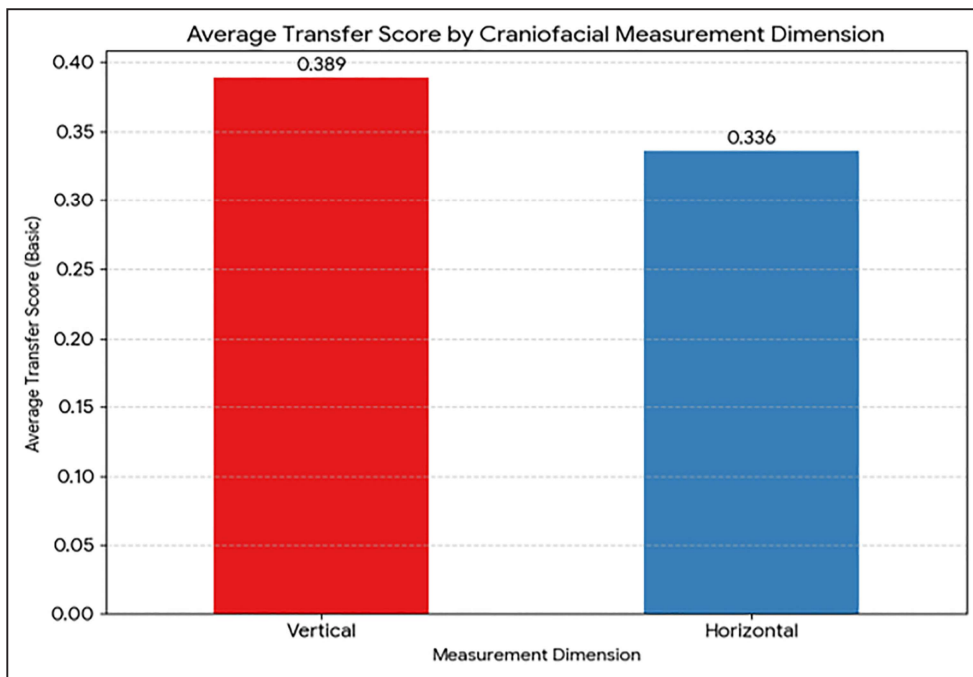


Figure 3: Comparison of average transfer scores between vertical and horizontal craniofacial dimensions

Sto-Sl, En-Ex, Zy-Zy became widespread consistent in inheritance and highly predictive resemblance carriers, which are highly (Figure 4).

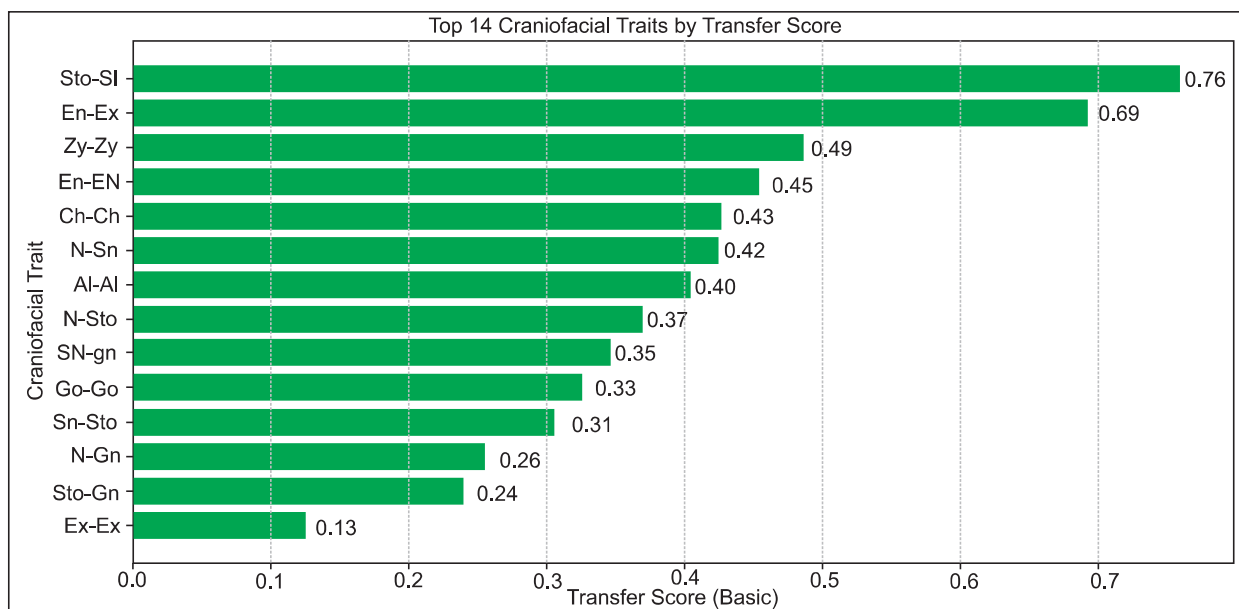


Figure 4: Ranking of craniofacial traits based on transfer score indicating resemblance strength

Concordance in heritability of biology and predictability in algorithms were high when machine-learning regression modelling was used. Very highly-heritable traits had

better predictive performance (R^2 to 0.65), and low-heritability traits had unstable predictions (Figure 5).

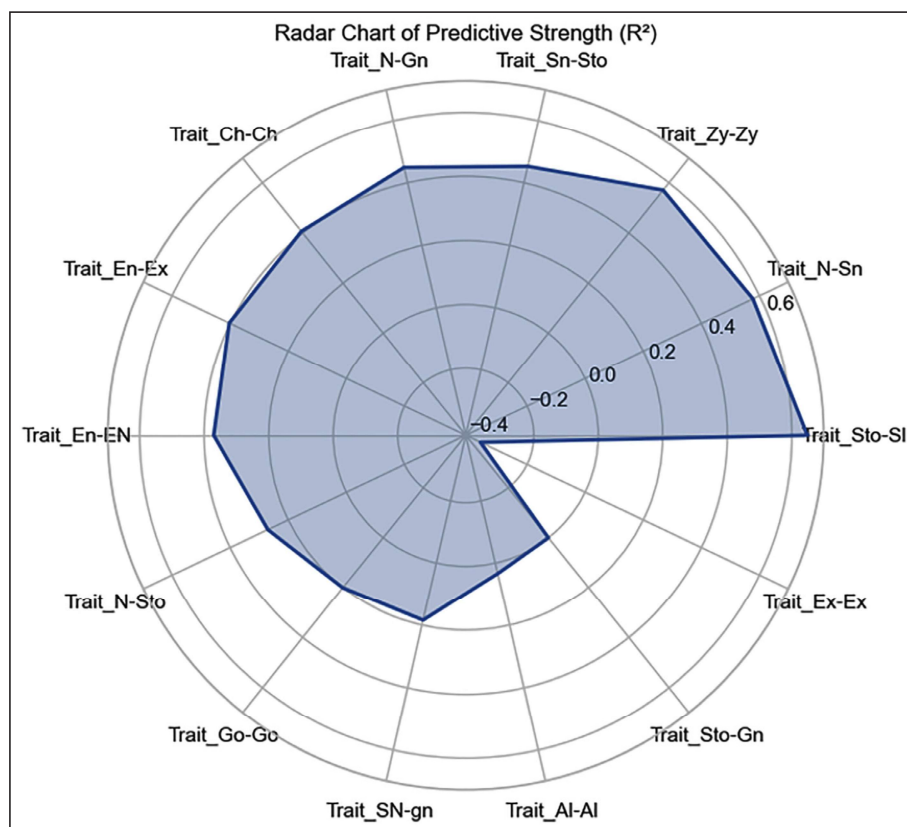


Figure 5: Radar plot illustrating AI-assisted predictive strength (R^2) of individual craniofacial traits

Such compatibility proves that biologically stable characteristics are better inputs to biometric systems based on AI.^{15,27,28}

DISCUSSION

The current research shows that craniofacial morphology is a hierarchically already organized biometric surface and not a homogeneous surface of the face. The results of this research aligned with previous research, which found high heritability of craniofacial traits in family-based studies.¹ This research also showed that vertical craniofacial dimensions exhibit greater generational stability and reduced biological variance, confirming their suitability for AI-assisted predictive modeling. These findings support the notion that biologically stable traits are more reliable for use in forensic analysis.

In comparison, horizontal features demonstrated lower heritability, which might limit their effectiveness in forensic applications.

Similar studies indicated that facial dimensions vary considerably across generations, but the consistency of vertical dimensions remains a strong predictor of biological inheritance.⁴⁻⁵

The results of this research emphasize the importance of incorporating biologically validated craniofacial features into AI-based forensic systems to ensure accuracy, reduce bias, and enhance the interpretability of facial biometric data in criminal investigations.

These findings are very important in a cyber and digital forensic perspective. Facial recognition technology based on the use of unstable soft-tissue characteristics is highly exposed to spoofing and cosmetic modification, as well as deepfakes.^{15,29}

Combining forensic anthropology and AI modelling creates a scientifically explainable biometric pipeline to meet the need of explainable AI in forensic science by the courts.¹⁵⁻¹⁷

CONCLUSION

This paper develops anthropometric-biologically anchored AI-assisted face biometrics of cyber and digital forensic practices. Craniofacial features do not inherit in a uniform manner, and the vertical dimensions of the face portray descent continuity, similarity transmission, and predictability of an algorithm.

The set of Sto-SI, En-Ex and Zy-Zy is found to be one of the fundamental forensic biometrics features that give biologically understandable and computationally sound input to the facial recognition systems.

DECLARATIONS

Ethics approval and consent to participate

Ethics approval for the study protocol was reviewed and discussed with the UCRD & RDC, Department of Forensic Science, Chandigarh University, Mohali, India. Informed verbal consent was obtained from all individual participants prior to data collection. Participation was voluntary, and all procedures were conducted in accordance with institutional ethical standards.

Conflict of Interest: Nil

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