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Quantitative Assessment of Facial Symmetry: A Standardised Geometric Morphometric Method Using Open-Source Landmark Data

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Abstract **Background:** Facial symmetry is a key metric in cosmetic and reconstructive facial assessment. Conventional evaluations rely predominantly on subjective visual judgment, lacking standardized, reproducible quantitative tools. This study aimed to develop an open-source geometric morphometric framework for 2D facial symmetry quantification and explore its association with demographic factors and perceived attractiveness. **Methods:** In this cross-sectional computational morphometric analysis, we used the public SCUT-FBP5500 dataset containing 5,500 frontal images with manually refined 86-point landmarks and attractiveness ratings from 60 independent assessors. A mid-sagittal reference line was estimated and the Geometric Symmetry Index (GSI) was defined as the mean normalized Euclidean distance between bilateral landmarks and their mirrored counterparts. Lower GSI values indicate greater geometric facial symmetry. Sex differences and attractiveness correlations were analysed via Welch's t-test and Spearman's rank correlation. **Results:** Valid GSI values were obtained for 5,499 subjects (one excluded for incomplete landmarks). The cohort showed generally high facial symmetry. Males exhibited significantly greater asymmetry than females (Cohen's d = 0.58, 95% CI: 0.52-0.63, $p < 0.001$). GSI had a modest but significant negative correlation with attractiveness ratings ($\rho = -0.277$, 95% CI: −0.302 to −0.253, $p < 0.001$). **Conclusion:** This interpretable, reproducible open-source framework avoids the black-box limitations of complex AI models, providing a standardized solution for objective facial symmetry measurement. With further clinical validation, it may support aesthetic surgery planning, postoperative outcome assessment and digital patient communication.

Key Words Facial Symmetry, Geometric Morphometry, Facial Attractiveness, Aesthetic Surgery, Quantitative Assessment, Facial Landmarks

INTRODUCTION

Facial symmetry is a core correlate of perceived facial attractiveness. Evolutionary theories propose it as an indicator of developmental stability, health status and genetic fitness, yet systematic reviews and large-scale empirical studies consistently demonstrate only a modest magnitude of this association [1,2] with inconsistent findings regarding sex-specific effect sizes and statistical significance [3]. In clinical practice, symmetry assessment is integral to preoperative planning and postoperative evaluation in cosmetic and reconstructive facial surgery. Despite its clinical relevance, routine assessments remain largely subjective, relying on visual inspection or manual measurements with limited reproducibility and objective standardization.

Facial asymmetry quantification has been addressed via both conventional geometric morphometry and modern AI approaches. Conventional asymmetry metrics include linear distance ratios, 2D area indices and landmark-aligned shape scores. Linear measures are intuitive but limited to isolated landmarks; global shape methods lack regional detail and require specialized software. Systematic reviews of AI applications in plastic surgery have documented increasing uptake in craniofacial and aesthetic practice, while noting that most studies remain preclinical, with heterogeneous validation metrics and limited generalizability [4]. For 3D facial scans, patch-based convolutional neural networks have achieved clinically viable landmark detection [5]. Although deep learning methods have been extensively reviewed

in facial beauty prediction literature [6], few studies have developed interpretable, clinically meaningful symmetry indices. Most existing AI approaches employ black-box models with limited clinical transparency and pixel-level mirroring techniques generally lack clear anatomical correspondence [4].

The publicly available SCUT-FBP5500 dataset provides a suitable basis for addressing these limitations. It comprises 5,500 high-quality frontal facial images with attractiveness ratings from 60 independent assessors and 86-point facial landmark annotations; landmarks are initially generated via an Active Shape Model and manually refined for high accuracy [7]. Three key knowledge gaps remain: first, there is a lack of fully interpretable, open-source symmetry metrics with clear anatomical correspondence; second, large-scale population reference data for landmark-based facial symmetry remain scarce; third, the magnitude of the symmetry-attractiveness association has not been quantified with a standardized geometric metric in a large cohort. Although the SCUT-FBP5500 dataset is widely used for attractiveness prediction, its granular landmark annotations have not been systematically leveraged to derive explicit geometric symmetry metrics.

This study aims to develop an open-source, interpretable geometric framework for facial symmetry quantification using the SCUT-FBP5500 dataset, propose the Geometric Symmetry Index (GSI) as a standardized metric and examine sex differences in facial symmetry and its association with perceived attractiveness to provide a reproducible quantitative tool for objective facial assessment in aesthetic and reconstructive practice.

METHODS

Study Design and Dataset

This cross-sectional secondary analysis of a publicly available anonymized dataset used the SCUT-FBP5500 cohort, comprising 5,500 standardized frontal facial images with manually refined 86-point landmarks and attractiveness ratings from 60 independent assessors. Landmark coordinates were first generated via an Active Shape Model and refined by trained annotators to ensure geometric accuracy, as validated in the original dataset publication [7]. Inter-observer variability in manual refinement remains a minor source of measurement error. All images with complete landmark data were included. As a secondary analysis of fully anonymized public data, no ethical approval was required.

Landmark Data Format and Extraction

Facial landmark data were stored as binary .pts files paired with each facial image. Each file uses a 32-bit binary format: an integer header specifying the landmark count, followed by floating point (x,y) coordinates for each landmark.

Coordinates were parsed directly from the binary files and reshaped into an N×2 matrix. For consistent input dimensions, only files with a minimum of 86 valid landmarks were retained and the first 86 points were used for all subsequent analyses. Images with incomplete or corrupted landmark files were excluded.

Coordinate Normalization

All pairwise asymmetry distances were normalized by a subject-specific facial scale factor to eliminate facial size effects, generating a dimensionless, scale-invariant symmetry index. The scale factor was computed as the Euclidean distance between centroids of the left and right landmark subsets. This method accounts for global facial width variation, is robust to individual landmark localization errors and follows standard scaling conventions in landmark-based morphometry.

Bilateral Landmark Pair Definition

All 86 landmarks correspond to bilaterally symmetric facial structures and were paired into 43 homologous pairs by anatomical homology across key aesthetic regions. The complete list of all 43 homologous pairs, with anatomical descriptions and facial region assignments, is provided in Table 1.

Mid-Sagittal Reference Line Estimation

A subject-specific mid-sagittal reference line was derived from bilateral landmark coordinates. Midpoints were computed for each homologous pair and the reference line was defined as the vertical line passing through the mean x-coordinate of all midpoints. This vertical approximation assumes near-frontal head orientation and is a standard robust midline approach in 2D morphometric studies. It remains sensitive to subtle yaw rotations, which may introduce minor measurement bias. Deviations from true frontal positioning also introduce projection asymmetry that distorts bilateral landmark distances. Standardized frontal image acquisition in the current dataset minimizes these sources of variation. Formal quantitative sensitivity analysis under controlled rotational perturbations is a priority for future method development.

Geometric Symmetry Index

Bilateral facial asymmetry was quantified using the proposed GSI. For each homologous pair, the right landmark was mirrored across the mid-sagittal reference line and the normalized asymmetry distance was calculated as the Euclidean distance between the left and mirrored right landmark, divided by the subject-specific facial scale factor. The GSI was defined as the mean normalized asymmetry across all bilateral landmark pairs:

$$\mathrm{GSI} = \frac{1}{N}\sum_{i=1}^{N} d_i$$

Where d_i denotes the normalized asymmetric distance for pair i and N is the total number of bilateral landmark pairs. Lower GSI values indicate greater geometric facial symmetry.

Table 1. Bilaterally Homologous Facial Landmark Pairs by Facial Region

Frontotemporal region	Eyebrows	Periorbital / Eyelids	Zygomatic & buccal contours	Nasal alae	Oral & labial region	Mandibular border
Temporal hairline	Eyebrow lateral tail	Lateral canthus	Zygomatic arch	Nasal alar groove	Oral commissure	Mandibular angle
Mid-lateral forehead	Mid-lateral eyebrow	Upper eyelid (lateral third)	Malar eminence	Nasal alar rim	Upper vermilion (lateral third)	Posterior mandibular body
Medial supraorbital ridge	Eyebrow apex	Upper eyelid margin	Infraorbital cheek	-	Upper vermilion (medial third)	Mid-mandibular body
Glabellar lateral margin	Mid-medial eyebrow	Medial canthus	Mid-cheek	-	Lower vermilion (medial third)	Anterior mandibular body
-	Eyebrow medial head	Lower eyelid margin	Buccal contour	-	Lower vermilion (lateral third)	Para-symphyseal mandible
-	-	Lower eyelid (lateral third)	Lower buccal contour	-	Upper lip inner border (lateral)	Lateral chin contour
-	-	-	-	-	Upper lip inner border (medial)	Mid-lateral chin
-	-	-	-	-	Lower lip inner border (medial)	Inferior chin margin
-	-	-	-	-	Lower lip inner border (lateral)	Medial inferior chin
-	-	-	-	-	-	Para-pogonion
-	-	-	-	-	-	Inferior para-symphyseal chin

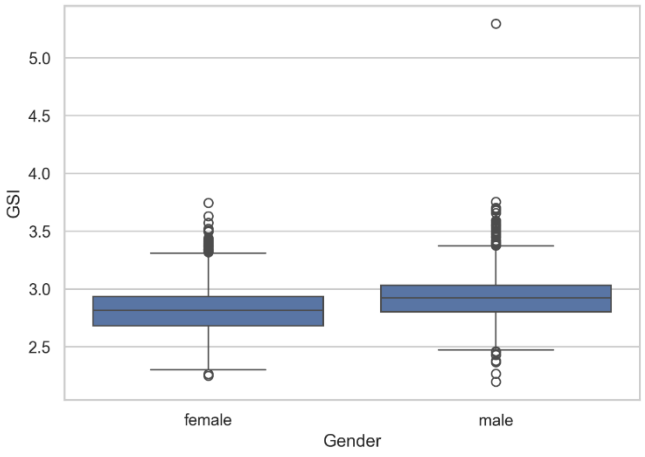


Figure 1: Distribution of Geometric Symmetry Index (GSI) values by gender.

Legend: Distribution of Geometric Symmetry Index (GSI) values by sex (n = 2749 males, n = 2750 females). Male GSI was significantly higher (Cohen's d = 0.58, 95% CI 0.52-0.63, p < 0.001). Boxplots represent the median and interquartile range, with whiskers indicating 1.5× the interquartile range. Individual points denote outliers. Lower GSI values correspond to greater geometric facial symmetry.

Demographic Variables and Attractiveness Ratings

Subject sex was inferred from the filename naming convention (second character: F for female, M for male), consistent with the dataset's official demographic grouping. Attractiveness scores were computed as the mean rating from 60 independent assessors using a 5-point ordinal scale and served as the outcome measure for analyses of symmetry and perceived attractiveness.

Statistical Analysis

Descriptive statistics were computed for GSI values across the full dataset.

Differences in GSI between male and female subjects were assessed using Welch's independent-samples t-test. A simple linear regression model was fitted with GSI as the dependent variable and sex as the independent variable to evaluate independent predictive value. The association between GSI and attractiveness scores was evaluated using Spearman's rank correlation coefficient. Effect sizes and 95% confidence intervals are emphasized over p-values, as statistical significance is expected in large cohorts. Statistical significance was defined as a two-tailed $p<0.05$.

Software Implementation and Reproducibility

All analyses were implemented in Python 3.11 and run on a standard workstation without GPU acceleration. Data processing and statistical analyses were performed using NumPy, Pandas and SciPy; visualizations were generated with Matplotlib and Seaborn. The full pipeline is reproducible, with intermediate outputs retained for validation. Random sample subsets were visually inspected to confirm accurate landmark parsing, pairing, midline estimation and symmetry calculation.

RESULTS

A total of 5,500 facial images with corresponding landmark files were initially screened. After excluding one image with incomplete landmark coordinates, valid GSI values were obtained for 5,499 subjects.

Gender Differences in Geometric Facial Symmetry

Among the subjects with valid GSI values, 2,749 were male and 2,750 were female. A statistically significant difference in GSI was observed between male and female subjects. Welch's independent sample t-test showed a medium effect size for sex differences in GSI (Cohen's d = 0.58, 95% CI 0.52-0.63, t = 21.33, $p = 4.37 \times 10^{-97}$). Linear regression confirmed sex as a significant predictor of GSI ($\beta = 0.11$, 95% CI 0.10-0.12, $p = 4.34 \times 10^{-97}$, $R^2 = 0.077$). Male subjects showed higher GSI values than female subjects. The distribution of GSI values by gender is illustrated in Figure 1.

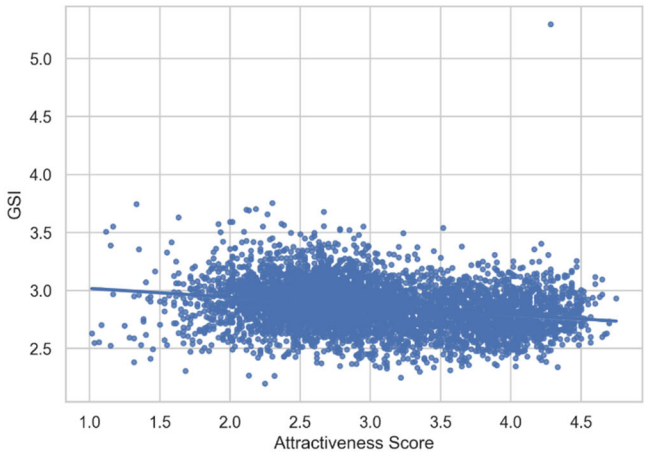


Figure 2: Scatter plot illustrating the relationship between Geometric Symmetry Index (GSI) and attractiveness score.

Legend: Scatter plot illustrating the relationship between Geometric Symmetry Index (GSI) and attractiveness score (n = 5499). Spearman's ρ = −0.277 (95% CI −0.302 to −0.253, p < 0.001). Each point represents one subject. The solid line indicates the fitted regression trend. Lower GSI values indicate greater facial symmetry.

Association Between Facial Symmetry and Attractiveness

Spearman correlation analysis revealed a weak-to-moderate statistically significant negative association between GSI and attractiveness ratings (ρ = −0.277, 95% CI −0.302 to −0.253, $p = 1.11 \times 10^{-97}$), indicating that facial symmetry explains only a small proportion of variance in perceived attractiveness. Lower GSI values, corresponding to greater geometric facial symmetry, were associated with higher perceived attractiveness scores. The relationship between GSI and attractiveness score is visualized in Figure 2.

DISCUSSION

This study presents a reproducible landmark-based geometric morphometric framework for quantifying facial symmetry from standard 2D frontal photographs. Using the large SCUT-FBP5500 dataset, we derived the Geometric Symmetry Index (GSI) to capture bilateral geometric deviations across multiple facial regions with full interpretability. Valid GSI values were obtained for 5499 of 5500 subjects, confirming the technical robustness and population-level scalability of landmark-based symmetry quantification.

With respect to sex differences, male faces exhibited significantly greater geometric asymmetry than female faces, corresponding to a medium effect size (Cohen's d = 0.58). The large sample size confers high statistical confidence in this difference, but substantial overlap in GSI distributions indicates only moderate sexual dimorphism, precluding reliable individual-level sex inference from global symmetry. This finding differs from prior linear morphometric work that reported no significant sex difference in facial asymmetry [8], which may be attributed to differences in measurement methodology and sample size.

Collectively, the evidence supports that GSI is a moderately dimorphic rather than strongly sex-specific trait. Whether facial symmetry and sexual dimorphism are independent aesthetic dimensions requires further targeted investigation.

Regarding the link between symmetry and perceived attractiveness, greater geometric facial symmetry corresponded to higher attractiveness ratings, with a modest but significant inverse correlation between GSI and attractiveness scores (ρ = −0.277). This is consistent with multifactorial models of facial attractiveness, in which symmetry contributes less explanatory power than averageness, the dominant factor [9,10]. Existing work indicates that theory-driven models built on classic factors (averageness, sexual dimorphism) explain more variance in female than male attractiveness, whereas data-driven face-space models perform consistently well across both sexes [11]. A recent large-scale study of natural faces found no significant association between shape symmetry and attractiveness in either sex, with averageness as a robust cross-sex predictor and femininity as a key predictor for female faces specifically [12]. Methodological differences likely explain this discrepancy. Our large sample detects the modest association with high statistical power.

Scatter plot visualization shows a clear negative trend alongside substantial dispersion, indicating that high symmetry alone does not guarantee high attractiveness and mild asymmetry does not preclude favourable aesthetic judgments. This pattern reflects the multifactorial nature of facial attractiveness, in which symmetry is one of many contributing factors alongside averageness, sexual dimorphism, skin texture and expressive features and has modest independent explanatory power. It may function as a baseline geometric prerequisite for overall facial harmony rather than a primary driver of attractiveness [9,10]. Ethnicity-related variation in facial morphology may also affect baseline symmetry levels and the magnitude of symmetry-attractiveness associations; the current cohort is predominantly East Asian and findings may not be directly generalizable to other ethnic groups.

From a methodological perspective, the proposed framework addresses key limitations of existing symmetry assessment approaches. Unlike black-box deep learning models widely used in facial analysis, GSI is derived from geometric operations on anatomically homologous landmarks, ensuring full interpretability and clinical transparency. GSI stability is tied to landmark localization precision, which declines at very low image resolutions; all images in the current dataset have consistent high resolution, ensuring reliable landmark detection. This aligns with recent consensus in aesthetic medicine emphasizing objective, standardized and reproducible quantitative metrics for clinical translation of AI tools [13]. Use of open-source data and standardized computational tools further improves reproducibility and

cross-study comparability. Head-to-head validation against established morphometric indices and formal test-retest reliability assessment remains required to fully characterize metric performance.

These features support potential future clinical applications in aesthetic and reconstructive surgery, pending prospective validation. All proposed applications remain hypothetical and unvalidated at this stage and the method is currently intended for research use only. If validated, objective symmetry quantification may complement subjective visual assessment in preoperative planning, support standardized postoperative outcome evaluation and enable longitudinal monitoring of facial changes. Quantitative symmetry metrics may also improve patient communication through intuitive numerical and graphical feedback, aligning with the shift toward shared decision-making in aesthetic care [14]. Validation in surgical, reconstructive and pathological facial cohorts is a necessary next step before clinical implementation.

This study has several limitations. First, analysis was restricted to 2D photographs, which do not capture depth or three-dimensional facial contour and are susceptible to measurement bias from subtle head rotations. Extension of the framework to 3D imaging data would further enhance clinical utility and methodological robustness. Second, the SCUT-FBP5500 dataset comprises predominantly East Asian facial phenotypes from a curated attractiveness-rated cohort, rather than unselected general or clinical populations. This introduces potential selection bias and limits generalizability to other ethnic groups as well as to diseased or postoperative patient populations. Third, the current GSI captures only global bilateral symmetry and has not been validated in independent external cohorts; test-retest reliability and performance across varying imaging conditions also remain to be established. Future work extending the metric to region-specific symmetry and conducting multi-cohort external validation would further strengthen its clinical applicability.

CONCLUSIONS

This study demonstrates that open-source facial landmark data can be used to derive a simple, interpretable and reproducible metric for facial symmetry quantification. Sex differences in geometric facial symmetry and its modest but robust association with perceived attractiveness support the validity of the proposed GSI as an objective aesthetic metric. With further validation in clinical populations and extension to three-dimensional imaging, this framework may aid the development of standardized tools for quantitative facial assessment in research and clinical practice.

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