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Three-dimensional Morphometric Analysis of the Zygomatic Arch and Temporozygomatic Suture: Implications for Asymmetry and Sexual Dimorphism

Arcus Zygomaticusun ve Sutura Temporozygomatica'nın Üç Boyutlu Morfometrik Analizi: Asimetri ve Cinsel Dimorfizm Açısından Değerlendirme

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ABSTRACT

Aim: The zygomatic arch (arcus zygomaticus) forms a critical anatomical bridge between the viscerocranium and neurocranium, contributing to facial width, aesthetics and masticatory biomechanics. The temporozygomatic suture, which connects the temporal and zygomatic components of the arch, plays an important role in midfacial stability and is frequently involved in surgical interventions. Despite its clinical relevance, detailed three-dimensional morphometric data regarding the localization and variability of this suture remain limited. The aim of this study was to evaluate the three-dimensional morphometric localization of the temporozygomatic suture along the zygomatic arch and to determine side- and sex-related differences.

Materials and Methods: This retrospective study was conducted using computed tomography–based three-dimensional reconstructions. Standardized orientation protocols were applied, and morphometric measurements were obtained to assess the localization of the temporozygomatic suture along the zygomatic arch. Analyses were performed with respect to side-related asymmetry and sex-related differences.

Results: The findings revealed significant sexual dimorphism in several projection-related parameters of the zygomatic arch. A consistent left-sided predominance was observed in the localization of the temporozygomatic suture and in measurements related to the temporal process of the zygomatic bone, whereas the zygomatic process of the temporal bone demonstrated relative stability across sexes and sides.

Conclusion: The results indicate that variability of the zygomatic arch is segment-specific and influenced by both sex and laterality. Recognition of these three-dimensional anatomical patterns may improve surgical planning, radiological interpretation, and forensic assessments involving the zygomatic and temporal regions.

Keywords: Zygomatic arch, zygoma, cephalometry, facial asymmetry

ÖZ

Amaç: Zigomatik ark (arcus zygomaticus), visserokranium ile nörokranium arasında kritik bir anatomik köprü oluşturarak yüz genişliği, estetik görünüm ve çiğneme biyomekaniğine katkıda bulunur. Zigomatik arkın temporal ve zigomatik bileşenlerini birleştiren temporozigomatik sütür, orta yüz stabilitesinde önemli bir rol oynar ve cerrahi girişimlerde sıklıkla yer alır. Klinik önemine rağmen, bu sütürün lokalizasyonu ve değişkenliğine ilişkin ayrıntılı üç boyutlu morfometrik veriler sınırlıdır. Bu çalışmanın amacı, temporozigomatik sütürün zigomatik ark boyunca üç boyutlu morfometrik lokalizasyonunu değerlendirmek ve taraf ile cinsiyete bağlı farklılıkları belirlemektir.

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Gereç ve Yöntemler: Bu retrospektif çalışma, bilgisayarlı tomografi temelli üç boyutlu rekonstrüksiyonlar kullanılarak gerçekleştirildi. Standartlaştırılmış oryantasyon protokolleri uygulandı ve temporozigomatik sütürün zigomatik ark boyunca lokalizasyonunu değerlendirmek amacıyla morfometrik ölçümler yapıldı. Analizler, taraflar arası asimetri ve cinsiyete bağlı farklılıklar açısından gerçekleştirildi.

Bulgular: Bulgular, zigomatik arkın projeksiyonuna ilişkin çeşitli parametrelerde belirgin cinsiyet farklılıkları olduğunu gösterdi. Temporozigomatik sütürün lokalizasyonunda ve zigomatik kemiğin temporal çıkıntısına ilişkin ölçümlerde tutarlı bir sol taraf baskınlığı saptanırken, temporal kemiğin zigomatik çıkıntısı cinsiyetler ve taraflar arasında göreceli olarak daha stabil bulundu.

Sonuç: Bulgular, zigomatik arkın değişkenliğinin segmente özgü olduğunu ve hem cinsiyet hem de taraf farklılıklarından etkilendiğini göstermektedir. Bu üç boyutlu anatomik paternlerin tanınması, zigomatik ve temporal bölgeleri ilgilendiren cerrahi planlamanın, radyolojik değerlendirmelerin ve adli tıp incelemelerinin geliştirilmesine katkı sağlayabilir.

Anahtar Kelimeler: Zigomatik ark, zigoma, sefalometri, yüz asimetrisi

INTRODUCTION

The zygomatic arch (arcus zygomaticus) is a prominent anatomical bridge connecting the viscerocranium to the neurocranium and plays a pivotal role in the structural integrity and transverse dimension of the facial skeleton[1-3]. Composed of the temporal process of the zygomatic bone (Z) and the zygomatic process of the temporal bone (TE), the arch contributes significantly to facial width and cheek prominence, rendering it a key structure in both facial aesthetics and reconstructive procedures such as reduction malarplasty[4,5]. Functionally, it serves as the primary origin site of the masseter muscle, transmitting substantial masticatory forces through the midface and thereby influencing regional bone morphology and cortical architecture[3,6,7].

The junction between the zygomatic and temporal components forms the temporozygomatic (zygomaticotemporal) suture, a laterally projecting articulation that is particularly vulnerable to traumatic injury[4,8]. Accurate knowledge of the topographic anatomy of this region is therefore essential for minimizing complications during maxillofacial surgical procedures, including zygomatic implant placement and osteotomies performed for facial reconstruction[4,9]. Despite its clinical importance, the temporozygomatic suture has received comparatively limited attention in morphometric research, particularly when contrasted with more extensively studied craniofacial sutures.

Advances in 3D imaging techniques, including computed tomography (CT) and cone-CT (CBCT), have markedly improved the precision of craniofacial morphometric analyses[10,11]. Previous three-dimensional imaging studies have demonstrated that craniofacial structures exhibit considerable age- and sex-related morphometric variability, particularly in anatomically complex regions, underscoring the necessity of precise three-dimensional localization[12,13]. Unlike traditional two-dimensional radiography, 3D reconstruction enables detailed visualization of sutural maturation and measurement of specific anatomical landmarks without distortion caused by superimposition[14,15]. These techniques have been facilitated the classification of zygomatic arch shapes and the assessment of symmetry in the midfacial region[3,15].

However, despite growing interest in the zygomatic complex, quantitative data regarding the precise three-dimensional localization of the temporozygomatic suture along the zygomatic arch remain scarce. While the maturation and morphology of the zygomaticomaxillary suture have been widely categorized[14], the temporozygomatic suture is often simplified as a linear junction in biomechanical models, despite evidence demonstrating its complex interdigitated structure and age-related morphological changes[6]. Although this suture is known to remain patent into late adulthood, frequently not fusing until the seventh decade of life, its positional variability within adult populations has not been sufficiently documented[5,8]. This lack of precise morphometric localization limits both biomechanical modeling and the reliability of surgical landmarks in the temporal fossa region.

Therefore, the aim of this study was to quantitatively evaluate the three-dimensional localization of the temporozygomatic suture along the zygomatic arch using CT-based reconstruction methods, with particular emphasis on side-related asymmetry and sex-related differences. By providing detailed morphometric data, this study seeks to enhance anatomical accuracy in forensic anthropology, improve preoperative planning in maxillofacial surgery, and contribute to the development of safer surgical approaches involving the temporal and zygomatic regions.

MATERIALS AND METHODS

Study Design and Sample Selection

This retrospective study was performed on cranial CT images. An a priori power analysis for the primary mixed-design model (F test, repeated measures within–between interaction) indicated a required total sample size of 34 ($f=0.25$, $\alpha=0.05$, power=0.80); the study included 50 subjects (27 males, 23 females) aged 18-77 years (43.93±13.48 in males, 40.57±16.19 years in females) who underwent CT examinations for various clinical indications at the Department of Radiology, Zonguldak Bülent Ecevit University Faculty of Medicine. CT datasets with adequate image quality and complete visualization of the zygomatic arch were included in the analysis. Subjects with a history of craniofacial trauma, congenital craniofacial anomalies, pathological bone lesions or prior surgical interventions involving the zygomatic or temporal region were excluded.

Ethical approval for the study was obtained from the Zonguldak Bülent Ecevit University Non-Interventional Clinical Research Ethics Committee (decision no: 2020/16-14, date: 05.08.2020), and the study protocol complied with the principles of the Declaration of Helsinki.

Image Processing and Three-Dimensional Reconstruction

All CT datasets were transferred to Horos software (version 4.0.0; open-source medical image viewer), where 3D reconstructions were generated using standardized thresholding protocols. To ensure consistency across measurements, all reconstructed skull models were reoriented prior to analysis. The Frankfort horizontal plane was used as the primary reference plane, and the median sagittal plane was established as the midline reference.

Measurements involving mediolateral distances relative to the midline were performed on the norma frontalis, whereas parameters related to the length and segmentation of the zygomatic arch were obtained on the norma lateralis, following optimal visualization of the arch contours and sutural landmarks.

Morphometric Measurements

For segmental measurements of the zygomatic arch, the sutura temporozygomatica was used as the anatomical junction separating the temporal process of the Z and the zygomatic process of the TE. For the Z measurement, the anterior endpoint was defined as the origin of the temporal process on the Z, and the posterior endpoint as the temporozygomatic suture. For the TE measurement, the anterior endpoint corresponded to the temporozygomatic suture, and the posterior endpoint to the root of the zygomatic process of the TE.

The temporozygomatic suture was identified on 3D reconstructions based on the anatomical junction between the temporal process of the Z and the zygomatic process of the TE. Localization was performed by examining the suture line on multiplanar reconstructions and confirming it on 3D surface renderings.

The following parameters were defined and measured bilaterally (R: right, L: left): the distance between the midline and the projection of the most prominent point of the zygomatic arch on the norma frontalis (R-MZ and L-MZ); the distance between the midline and the most medial point of the outer border of the zygomatic process of the frontal bone (R-MF and L-MF); the total length of the zygomatic arch (RT and L-T); the length of the zygomatic process of the temporal bone (R-TE and L-TE); and the length of the temporal process of the zygomatic bone (R-Z and L-Z).

All measurements were performed as linear (straight-line) distances between predefined anatomical landmarks using the measurement tools embedded within the Horos software environment and recorded in millimeters.

Statistical Analysis

Statistical analyses were performed using GraphPad Prism version 10.6.1 (GraphPad Software, San Diego, CA, USA). The normality of data distribution was assessed using the Shapiro–Wilk test. Because the right and left anatomical measurements were obtained from the same individuals, these data were evaluated as paired samples. Accordingly, normally distributed paired data were analyzed using the paired t-test and are presented as mean ± standard deviation (mean ± SD), whereas non-normally distributed paired data were analyzed using the Wilcoxon signed-rank test and are presented as median (25^{th}-75^{th} percentile).

Comparisons between male and female groups, which consisted of independent samples, were performed according to data distribution. Normally distributed data were analyzed using the unpaired t-test with Welch's correction and are presented as mean ± SD. Non-normally distributed data were analyzed using the Mann-Whitney U test and are reported as median (25^{th}-75^{th} percentile). When data distributions differed between groups, non-parametric tests were preferred.

Age comparisons between male and female participants were performed using the independent samples t-test after confirming normality. A p-value of less than 0.05 was considered statistically significant.

All measurements were performed by a single experienced observer under blinded conditions with respect to the patients' sex and age. To assess intraobserver reliability, the same observer repeated the measurements on a randomly selected subset corresponding to approximately 20% of the sample after an interval of two weeks. The intraclass correlation coefficient, based on a two-way mixed-effects model with absolute agreement, was 0.991, demonstrating excellent measurement consistency. Interobserver reliability was not evaluated in this study.

RESULTS

The study population consisted of adult male and female subjects, and morphometric measurements of the zygomatic arch and its components were evaluated with respect to side-related asymmetry and sex-related differences. The mean age of the women was 40.57±16.19 years, whereas the mean age of the men was 43.93±13.48 years, with no statistically significant difference between the groups (p=0.4269).

Analysis of mediolateral projection parameters demonstrated a consistent left-sided predominance of the zygomatic arch in both sexes. In female subjects, the distance from the median line to the most prominent point of the zygomatic arch (L-MZ: 64.92±2.687) was significantly greater than the corresponding right-side measurement (R-MZ: 62.46±3.43) ($p=0.001$). A similar pattern was observed in males, with L-MZ values [70.30 (67.00-71.80)] exceeding R-MZ values [68.80 (65.30-70.40)] ($p=0.0276$). When sex-based comparisons were performed, both R-MZ and L-MZ values were significantly greater in males than in females (both $p<0.001$), indicating a more laterally prominent zygomatic arch configuration in males (Figure 1).

A comparable left-sided predominance was identified for the distances from the median line to the most medial point of the outer border of the frontal zygomatic process. In females, L-MF (48.57±2.191) was significantly greater than R-MF (47.23±2.523) ($p=0.0012$). In males, L-MF 50.99±2.167 was likewise significantly greater than R-MF 50.07±2.089 ($p=0.0194$). Furthermore, both R-MF and L-MF values were significantly greater in males compared with females ($p<0.0001$ and $p<0.0003$, respectively), further supporting the presence of sex-related differences in lateral facial projection (Figure 1 and Table 1).

In contrast to these projection-related parameters, no statistically significant side-related differences were detected in the total length of the zygomatic arch in either sex. In females, R-T (44.20±4.252) and L-T (44.38±5.190) values were comparable, and a similar bilateral symmetry was observed in males, with no significant difference between R-T [49.10

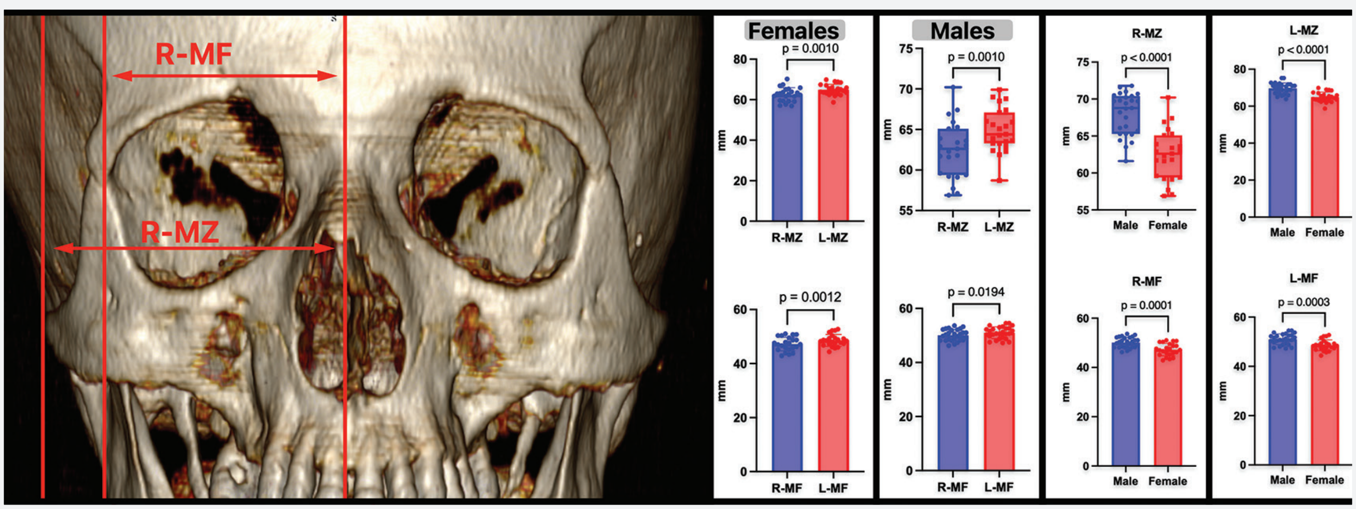

Figure 1. Assessment of mediolateral projection of the zygomatic arch and sex-based comparisons

R-MZ: Right midline-to-zygomatic bone distance, L-MZ: Left midline-to-zygomatic bone distance, R-MF: Right midline-to-frontal bone zygomatic process distance, L-MF: Left midline-to-frontal bone zygomatic process distance

Table 1. Comparison of morphometric parameters according to side (right vs. left) and sex

	Female	Female p (R-L)	Male	Male p (R-L)	p (Female-Male)
R-MZ	62.46±3.432	**0.0010**	68.80 (65.30-70.40)	**0.0276**	**<0.0001**
L-MZ	64.92±2.687		70.3 (67.0-71.80)		**<0.0001**
R-MF	47.23±2.523	**0.0012**	50.07±2.089	**0.0194**	**<0.0001**
L-MF	48.57±2.191		50.99±2.167		**0.0003**
R-T	44.20±4.252	0.8003	49.10 (46.10-49.80)	0.3895	**0.0017**
L-T	44.38±5.190		48.10 (45.10-51.30)		**0.0318**
R-TE	35.91±4.063	0.7867	38.10 (36.40-41.40)	**0.0001**	0.1299
L-TE	36.10±3.934		36.20 (31.10-38.80)		0.6960
R-Z	8.296±1.774	0.9773	8.50 (7.40-12.10)	**0.0003**	0.1386
L-Z	8.283±2.401		10.50 (8.30-14.50)		**0.0039**

Data are presented as mean ± standard deviation or median (25^{th}-75^{th} percentile), depending on data distribution. Paired comparisons were performed using paired t-test or Wilcoxon signed-rank test. Between-group comparisons were performed using unpaired t-test or Mann-Whitney U test, as appropriate, R-MZ: Right midline-to-zygomatic bone distance, L-MZ: Left midline-to-zygomatic bone distance, R-MF: Right midline-to-frontal bone zygomatic process distance, L-MF: Left midline-to-frontal bone zygomatic process distance

(46.10-49.80)] and L-T [48.10 (45.10-51.30)]. However, sex-based comparisons revealed that total arch length was significantly greater in males than in females on both sides (p=0.0017 and p=0.0318, respectively) (Figure 2 and Table 1).

Evaluation of the length of the zygomatic process of the TE demonstrated no significant side-related differences in either sex. In females, R-TE (35.91±4.063) and L-TE (36.10±3.934) values did not differ significantly, and a similar finding was obtained in males, in whom R-TE [38.10 (36.40-41.40)] and L-TE [36.20 (31.10-38.80)] were comparable. In addition, no statistically significant differences were observed between males and females for either R-TE or L-TE (Figure 2 and Table 1).

In contrast, analysis of the temporal process of the Z revealed a distinct pattern. While no significant difference was observed between R-Z (8.296±1.774) and L-Z (8.283±2.401) in females, male subjects exhibited a significantly greater L-Z [10.50 (8.30-14.50)] length than R-Z [(8.50 (7.40-12.10)] (p=0.0003), indicating a left-sided predominance specific to the male group. When sex-based comparisons were performed, no significant difference was observed for R-Z values; however, L-Z values were significantly greater in males than in females (p=0.0039) (Figure 2 and Table 1).

Overall, the results indicate that side-related asymmetry of the zygomatic arch was observed primarily in projection-related parameters and the temporal process of the Z, with a pronounced left-sided dominance, particularly in males. In contrast, the zygomatic process of the TE exhibited relative symmetry and did not show significant sex-related variation.

DISCUSSION

The morphological architecture of the zygomatic complex plays a pivotal role in facial esthetics and biomechanics, serving as a primary buttress for masticatory loads and a key determinant of facial width. Our morphometric study provides a detailed three-dimensional morphometric evaluation of the zygomatic arch and the temporozygomatic suture, revealing distinct patterns of sexual dimorphism and side-related asymmetry. By analyzing both projection-related parameters and the individual components of the zygomatic arch, our findings extend existing knowledge beyond traditional linear craniofacial measurements and offer anatomically meaningful insights with direct clinical relevance.

Sex-related differences constituted a prominent feature of our results. Measurements reflecting the mediolateral projection of the zygomatic arch were consistently greater in males than in females, supporting previous reports that identify the zygomatic region as one of the most sexually dimorphic areas of the craniofacial skeleton[3,7,10]. While earlier studies have largely focused on global indices such as bizygomatic width, the present analysis demonstrates that this dimorphism is not uniformly distributed across the arch. Specifically, elongation of the temporal process of the Z, rather than the zygomatic

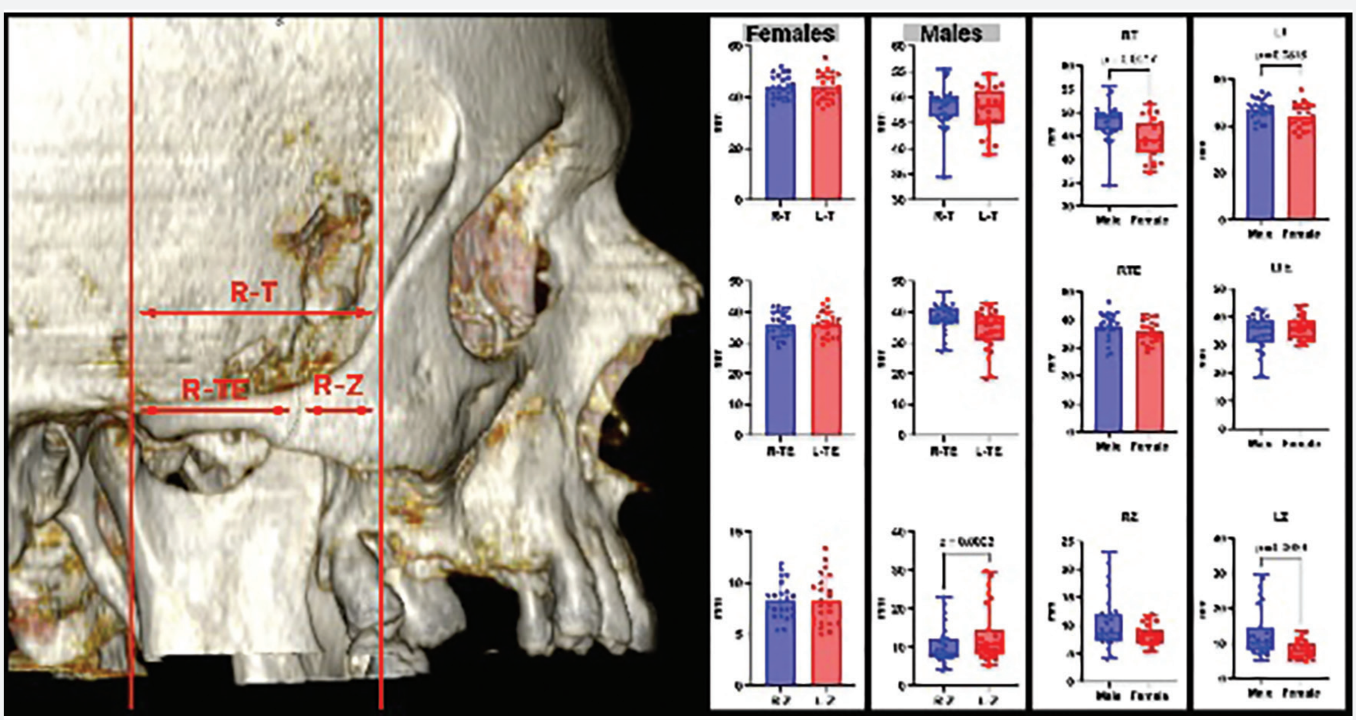

Figure 2. Morphometric analysis of zygomatic arch length and its components according to side and sex

process of the TE, appears to contribute more substantially to the observed sex differences. This finding aligns with geometric morphometric evidence suggesting that sexual dimorphism in the zygomatic region is expressed through complex surface remodeling rather than simple linear expansion[7].

A notable finding of this study is the consistent left-sided predominance observed in projection-related measurements and, in males, in the temporal process of the Z. Facial asymmetry is a well-recognized biological phenomenon, and perfect bilateral symmetry is rare in the human craniofacial skeleton[16,17]. Supporting this notion, Özen et al.[5] demonstrated significant side-related differences in the localization of the temporozygomatic suture, with a tendency toward a more anterior positioning on the left side of the zygomatic arch. Such asymmetrical sutural localization may contribute to differential segmental growth or remodeling of the arch components observed in the present study. In contrast, some cadaveric and radiological investigations have reported relatively symmetrical configurations of the zygomatic arch[4], suggesting that patterns of asymmetry may be population-specific and highly dependent on the anatomical landmarks and measurement strategies employed.

The asymmetrical elongation of the temporal process of the Z observed predominantly in males warrants particular consideration. The temporozygomatic suture is known to exhibit increasing interdigitation complexity with age and to respond dynamically to biomechanical forces transmitted by the masseter muscle and temporal fascia[6]. In this context, three-dimensional analyses have demonstrated that the morphology of the zygomatic arch is closely related to the functional demands of the masticatory system, particularly the orientation and force vectors of the masseter muscle[3]. Given that the Z serves as a primary attachment site for the masseter muscle, differential masticatory loading may preferentially influence remodeling of this component rather than the TE. Additionally, variability in the number and fusion patterns of zygomatic ossification centers may contribute to individual and side-related differences in adult morphology[18].

From a clinical perspective, the present findings have important implications for maxillofacial surgery, radiological assessment, and forensic analysis. In reconstructive procedures involving the zygomatic arch, the contralateral side is frequently used as a template for restoration. Our results suggest that such an approach may lead to underestimation of projection or segment length, particularly in male patients with pronounced left-sided dominance. This observation is consistent with recent recommendations emphasizing the need for sex-specific and side-aware planning in craniofacial surgery[11].

Furthermore, the stability of the zygomatic process of the TE across sexes and sides makes it a potentially more reliable surgical landmark than the variable zygomatic component. This is pertinent for procedures involving the zygomatic arch, where precise osteotomies are required to avoid complications such as trismus or facial asymmetry[4]. The structural variability of the Z also has implications for zygomatic implant placement, where understanding the specific dimensions of the zygomaticomaxillary complex is crucial to avoid injury to the orbit or infratemporal fossa[9].

Study Limitations

The present study is subject to certain limitations. The retrospective and cross-sectional design precludes evaluation of longitudinal changes in zygomatic arch asymmetry across different developmental stages. In addition, functional factors such as dental status, occlusal patterns, and habitual masticatory side preference were not assessed and may influence regional bone remodeling. In addition, a normalized positional index was not calculated; therefore, size-independent comparisons between individuals could not be performed. Future studies incorporating larger, population-diverse cohorts and advanced approaches such as dense surface morphometrics, normalization techniques, and finite element modeling may further elucidate the biomechanical mechanisms underlying the asymmetry patterns identified in this study.

CONCLUSION

This study provides a comprehensive three-dimensional morphometric analysis of the zygomatic arch, demonstrating clear patterns of sexual dimorphism and side-related asymmetry, particularly in projection-related parameters. The preferential involvement of the temporal process of the Z, contrasted with the relative stability of the zygomatic process of the TE, highlights the segment-specific nature of zygomatic arch variability. These findings underscore the importance of sex- and side-aware evaluation in surgical planning, forensic assessment, and radiological interpretation of the zygomatic region. A refined understanding of these anatomical characteristics may contribute to improved accuracy and safety in procedures involving the zygomatic arch.

Ethics

Ethics Committee Approval: Ethical approval for the study was obtained from the Zonguldak Bülent Ecevit University Non-Interventional Clinical Research Ethics Committee (decision no: 2020/16-14, date: 05.08.2020), and the study protocol complied with the principles of the Declaration of Helsinki.

Informed Consent: This is a retrospective study. Declaration on the Use of Artificial Intelligence.

AI-Assisted Technologies: During the preparation of this manuscript, the authors made limited use of the OpenAI ChatGPT language model to improve linguistic clarity, academic phrasing, and grammatical accuracy of the text. All AI-generated suggestions were critically reviewed and validated by the authors prior to inclusion. The authors take full responsibility for the scientific content, data analysis, interpretation of results, and the final version of the manuscript. The use of artificial intelligence did not influence the study data, analyses, or conclusions.

Footnotes

Authorship Contributions

Concept: K.A., Design: C.M.Ö., N.K., Data Collection or Processing: K.A., A.Z.Y.K., N.K., Analysis or Interpretation: C.M.Ö., A.Z.Y.K., Literature Search: C.M.Ö., N.K., Writing: K.A., A.Z.Y.K.

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