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Craniofacial/Pediatric

Automated 3D Analysis of Zygomaticomaxillary Fracture Rotation and Displacement

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Background: The zygomaticomaxillary complex (ZMC) can experience a multitude of deforming forces. There is limited understanding on which deformities alter patient outcomes. This study utilized an automated, three-dimensional analysis to elucidate which fracture patterns and rotational deformities are most prevalent and associated with postoperative complications.

Methods: This study was a 7-year retrospective review of patients with unilateral ZMC fractures who underwent surgical intervention. Patient demographics, injury mechanisms, presenting symptoms, and postoperative outcomes were collected. Segmentation was completed using Mimics software. The lateral-medial, superior-inferior, and anterior-posterior axes were manually identified on the zygoma and then displacement, rotational direction, and rotational degrees were automatically calculated using Geomagic software. Total displacement score was generated by summation of individual displacement scores at each of the five sutures.

Results: Eighty-one patients satisfied inclusion criteria. The most prevalent rotational pattern of the zygoma was medially-superiorly-posteriorly ($P < 0.001$). When comparing rotation along the three axes, the zygoma had the greatest rotation along the lateral-medial axis compared with the superior-inferior ($P = 0.003$) and anterior-posterior ($P < 0.001$) axes. Within each axis, the zygoma was more likely to rotate medially than laterally ($P = 0.003$) and posteriorly than anteriorly ($P = 0.01$). Multivariate analysis identified total displacement scores and degrees rotated along the lateral-medial axis as significant predictors of facial complications and reoperation.

Conclusions: This study suggests that patients with unilateral ZMC fractures who undergo surgical intervention are at an increased risk for adverse outcomes with greater rotation along the lateral-medial axis and higher total displacement scores. Additionally, the automated analysis method described can provide objective data to better characterize ZMC fractures. *(Plast Reconstr Surg Glob Open 2021;9:e3888; doi: 10.1097/GOX.0000000000003888; Published online 25 October 2021.)*

INTRODUCTION

The zygomaticomaxillary complex (ZMC) is one of the most frequently encountered midface fractures.[1] Due to its unique position on the face, the ZMC is prone to deformation with any facial trauma. Surgical treatment of ZMC fractures focuses on returning the ZMC to its native position to ensure proper malar projection while restoring native globe anatomy to preserve ocular function.

Clinical workup entails identifying fracture sites utilizing both physical examination and radiographic images, and identifying sites requiring reduction and fixation. Although computed tomography (CT) scans provide rapid images to identify fractures, quantifying the degree of displacement and rotation can be challenging, even with a three-dimensional (3D) rendering. Numerous variables can alter how the ZMC is displaced and rotated, including mechanism of injury, velocity of the injury, and area of maximal force.[2,3] A fracture at the zygomaticomaxillary buttress maybe visible on a CT scan; however, involvement and displacement of the adjacent zygomaticofrontal suture, zygomatic arch, and lateral orbit at the zygomaticosphenoid junction may vary widely depending on whether the zygoma is rotated medially or laterally.

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Several schematics have been developed to rapidly categorize ZMC fractures using fracture patterns or imaging to assess their clinical implications.[4–8] Improved image quality and slice thickness secondary to advancements in CT resolution have allowed for complex analyses using 3D renderings. There have only been a few reports that studied the ZMC using three-dimensional analytics.[9,10] These studies utilized different techniques to measure ZMC displacement and rotation. Both studies measured displacement and rotation manually on small cohorts, and only one study[9] evaluated the correlation between displacement and requiring surgical intervention. Neither study analyzed postoperative complications.

In this study, we sought to validate an automated technique to calculate ZMC displacement, rotational direction, and rotational distance. Additionally, we expand on prior studies by providing clinical correlations to illustrate which factors have the greatest impact on patient outcomes after surgical intervention.

Takeaways

Question: Can an automated technique be utilized to characterize ZMC fractures? What rotations and displacements result in increased risk for postoperative complications?

Findings: A 7-year retrospective review of patients with unilateral ZMC fractures yielded 81 patients who satisfied the inclusion criteria. The ZMC is most often rotated medially, superiorly, and posteriorly. Increased total displacement score and rotation along the lateral-medial axis was associated with higher rates of postoperative complications on multivariate analysis.

Meaning: Automated analysis of unilateral ZMC fractures suggests that patients with increased lateral-medial rotation and total displacement scores are at a higher risk for postoperative complications.

METHODS

Data Collection

After approval by an institutional review board, a retrospective cohort was assembled for patients with ZMC fractures who had preoperative CT face scans between 2012 and 2019 at a single, level 1 trauma center. Patients were excluded if they had bilateral trauma, severely comminuted injuries to the zygomatic body, or had CT scans with slice thickness greater than 0.65 mm. Patient demographics, injury mechanisms, presenting symptoms, and postoperative outcomes were collected. If patients were intubated or uncooperative for subjective symptoms, such as diplopia, they were excluded from the symptom totals. All patients underwent surgical correction of their fractures.

The five articulation points of the ZMC were defined as follows:

1. ZM1: infraorbital rim
2. ZM2: zygomaticomaxillary buttress
3. ZF: zygomaticofrontal junction
4. ZS: zygomaticosphenoid junction or lateral orbital wall
5. ZT: zygomaticotemporal junction or zygomatic arch

With historically poor patient followup in the trauma population, we organized patient complications into three composite groups to provide broad categories of the most important sequelae:

1. Orbital complications: diplopia greater than 2 weeks postoperatively and enophthalmos
2. Facial complications: lagophthalmos, ectropion, ptosis, facial motor weakness, trismus, and persistent malar depression
3. Reoperations

Segmentation

The digital model process illustrated in Figure 1A began with a preoperation spiral CT scan (Siemens Somatom Definition Flash). DICOM (Digital Imaging and Communications in Medicine) images from the scanner were imported into Mimics (Research v 21.0, Materialise, Leuven, Belgium) for segmentation of the skull. A mask created using the "Bone CT" threshold (226-3071 HU) was used to isolate the bone material from the surrounding soft tissue based on variations in Hounsfield units. The mask was manually edited to remove artifacts. A 3D object of the bone mask was generated and exported as a standard tessellation (STL) file. This STL file was imported into Geomagic (2014, 3D Systems, Rock Hill, S.C.), in which a smoothing operation was performed. A coordinate system was manually established and defined using the X-Y-Z axes as shown in Figure 1B. This also established the medial, sagittal, and coronal planes. The anterior (A)-posterior (P) axis was defined as the x-axis, the superior (S)-inferior (I) axis was defined as the y-axis, and the lateral (L)-medial (M) axis was defined as the z-axis.

The intact nontrauma side was isolated and a mirror function across the mid-sagittal plane was performed. The skull model was further isolated approximately 30 mm superiorly of the orbit, inferiorly to include a portion of the upper dentition, and posteriorly to include the full zygomatic arch.

Best Fit Analysis—Rotational Pattern and Degrees Rotated

Within Geomagic Studios, the ZMC from the mirrored model representing perfect symmetry was isolated, as shown in Figure 1C. The isolated ZMC was aligned with the contralateral, fractured ZMC through a best fit function, which is an implementation of an iterative closest point method. This method calculates a centroid, or geometric center, of the non-trauma zygoma and iteratively translates and rotates it until it finds the best alignment. The data generated are the direction and degrees rotated to achieve the best fit. An example alignment of the ZMC is shown in Figure 1D, demonstrating how medial, superior, and anterior rotation of the mirrored zygoma is required to attain the best fit.

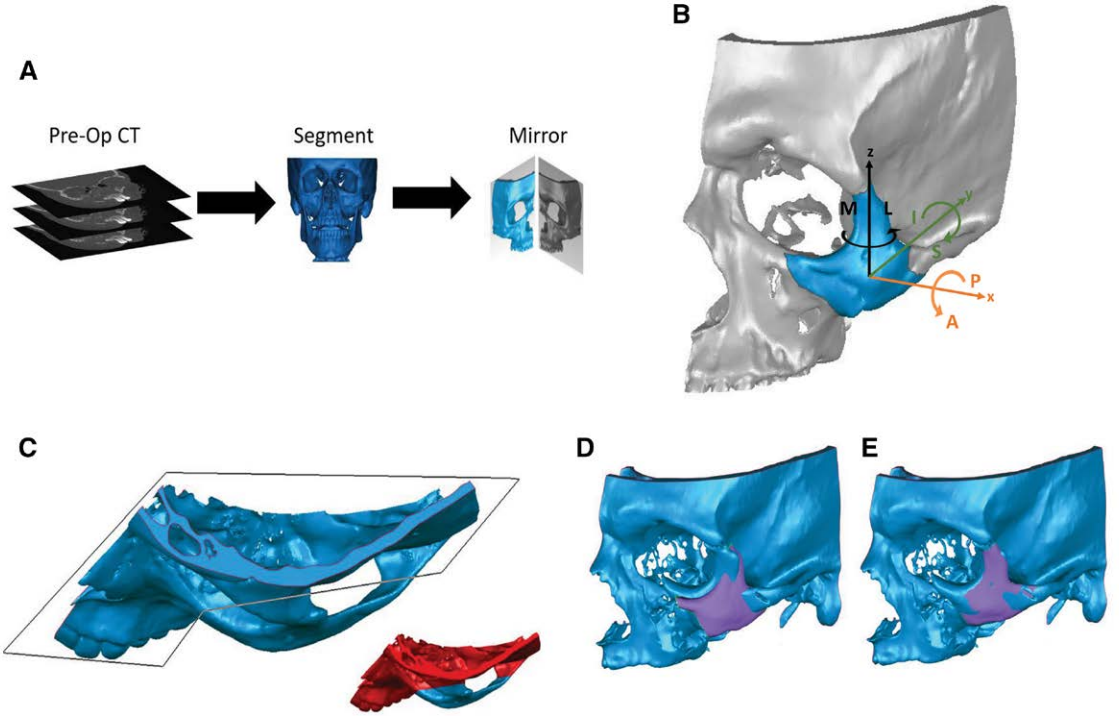

Fig. 1. Segmentation and best fit analysis method. A, Digital model process of anatomical models for unilateral trauma. B, Anatomical coordinate system defined on a 3D model. C, Isolation of the ZMC using a top axial view. The components within the box become selected, as shown in red, and then deleted, leaving an isolated ZMC. D, The patient's nontrauma mirrored ZMC (purple) at home position overlying the fractured site. E, After best fit alignment of the ZMC to the preoperative model. A: anterior; P: posterior; S: superior; I: inferior; L: lateral; M: medial.

Best Fit Analysis—Suture Displacement

Suture-specific displacement is obtained similarly to rotation except that the five ZMC sutures on the nontrauma, mirrored zygoma are selected for instead of the zygomatic body (Fig. 2A, B). The displacement is then calculated at the predefined suture points to yield an average displacement score (Fig. 2C).

In summary, if the nontrauma mirrored ZMC travels farther or rotates more to align with the fractured ZMC, then the values returned will be greater. As a result, the data generated represents the quantitative displacement at each of the five sutures and the rotational pattern and rotational distance, in degrees, of the ZMC body along the anterior-posterior axis, lateral-medial axis, and superior-inferior axis (Fig. 3). A total displacement score was calculated by summation of the displacement values at each suture.

Statistical Analysis

Patient demographics and fracture characteristics were described using means ± SDs for continuous variables and percentages for categorical variables. Paired *t*-tests were used

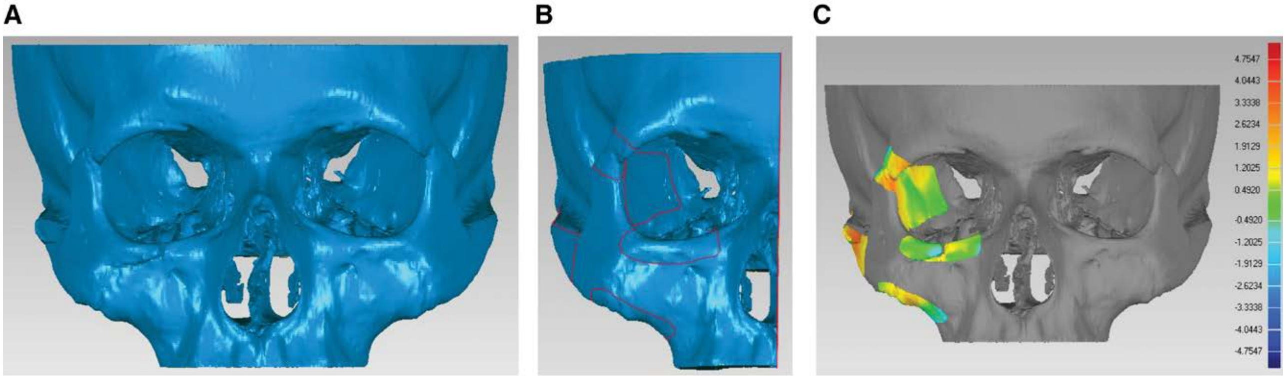

Fig. 2. Calculation of suture displacement. A, Right-sided ZMC fracture. B, Mirrored, nontrauma zygoma with the five suture points outlined. C, Heatmap indicating displacement distances between the fractured and mirrored zygoma.

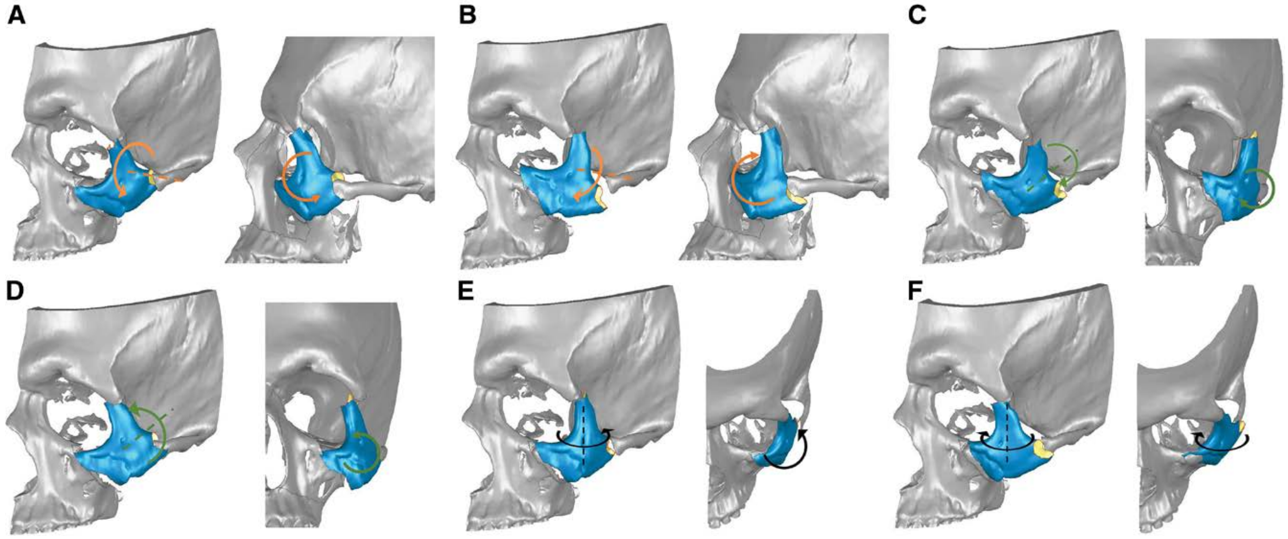

Fig. 3. Example of rotation patterns on a left-sided ZMC fracture. A, Anterior rotation; B, Posterior rotation; C, Superior rotation; D, Inferior rotation; E, Lateral rotation; and F, Medial rotation.

for analysis of displacement and rotation. A log-linear analysis was used to evaluate which rotational pattern was most prevalent. Multivariable logistic regression models were then constructed to determine the key predictors of orbital complications, facial complications, and reoperation. All models adjusted for age, time to operation, preoperative symptoms, and choice of approach to the infraorbital rim and/or orbital floor. All statistical analyses were performed using R Statistical Software (version 1.1.447; R Foundation for Statistical Computing, Vienna, Austria), and a P value less than 0.05 was considered statistically significant.

RESULTS

Patient Characteristics

A total of 93 patients had unilateral ZMC fractures, of which 12 were excluded for the absence of a CT face (n = 2), extensive injury to the zygoma body (n = 3), and inadequate CT slice thickness (n = 7). This yielded 81 patients who satisfied the criteria for inclusion (Table 1). The mean age at the time of presentation was 38.9 years, with nearly half of the patients endorsing current tobacco use (48.8%). Motor vehicle accidents (50.6%) were the most common mechanism of injury, and diplopia (55.3%) was the most common presenting symptom.

Table 1. Patient Demographics and Preoperative Symptoms

Patient Characteristics	
Patients, n	81
Age, mean ± SD (range)	38.9 ± 15.0 (3.7–79.0)
Tobacco use, n (% of total)	40 (48.8)
Mechanism of injury, n (% of total)	
MVA	41 (50.6)
Assault	19 (23.5)
Blunt trauma	10 (12.3)
Fall	8 (9.9)
GSW	3 (4.9)
Preoperative findings, n (% of total)	
Diplopia	26 (55.3)
Malar depression	21 (25.9)
Trismus	14 (23.0)
Enophthalmos	7 (8.6)
Facial motor weakness	1 (1.2)

GSW: gunshot wound; MVA: motor vehicle accident.

Fracture Characteristics

The ZM2 (4.52 mm) and ZM1 (4.47 mm) had the highest average displacement distances (Fig. 4). When compared with the ZF, all other sutures experienced significantly more displacement. The ZM1 [$P < 0.001$; 95% CI (0.56, 1.2)], ZM2 [$P < 0.001$; 95% CI (0.54, 1.33)], and ZT [$P = 0.005$; 95% CI (0.16, 0.87)] had higher displacement values compared with the ZS. There was no significant difference in displacement between the ZM1, ZM2, and ZT, although the ZM2 approached significance when compared against the ZT [$P < 0.09$; 95% CI (−0.07, 0.90)]. The average total displacement for ZMC fractures was 19.65 ± 11.20 mm.

In terms of rotational patterns, the zygoma was most often medially-superiorly-posteriorly rotated ($G^2 = 23.33$; $P < 0.001$) (Fig. 5). The least common rotational patterns were laterally-superiorly-anteriorly rotated and medially-inferiorly-anteriorly rotated.

To analyze the zygoma rotation along the three axes, the absolute value of degrees rotated was averaged for each of the three axes. The zygoma was rotated on average 2.68 ± 1.83 degrees in the anterior-posterior plane, 3.04 ± 2.65 degrees in the superior-inferior plane, and 4.51 ± 3.88 degrees in the lateral-medial plane. Statistical analysis of rotational distances between the three axes showed significantly greater rotation along the lateral-medial axis when compared with the anterior-posterior axis [$P < 0.001$; 95% CI (0.89, 2.77)] and the superior-inferior axis [$P = 0.003$; 95% CI (0.50, 2.44)]. When comparing rotational distances within each axis, the posterior rotation was significantly more than anterior rotation [$P = 0.01$; 95% CI (0.15, 1.89)], and medial rotation was significantly more than lateral rotation [$P = 0.003$; 95% CI (0.66, 4.02)] (Fig. 6).

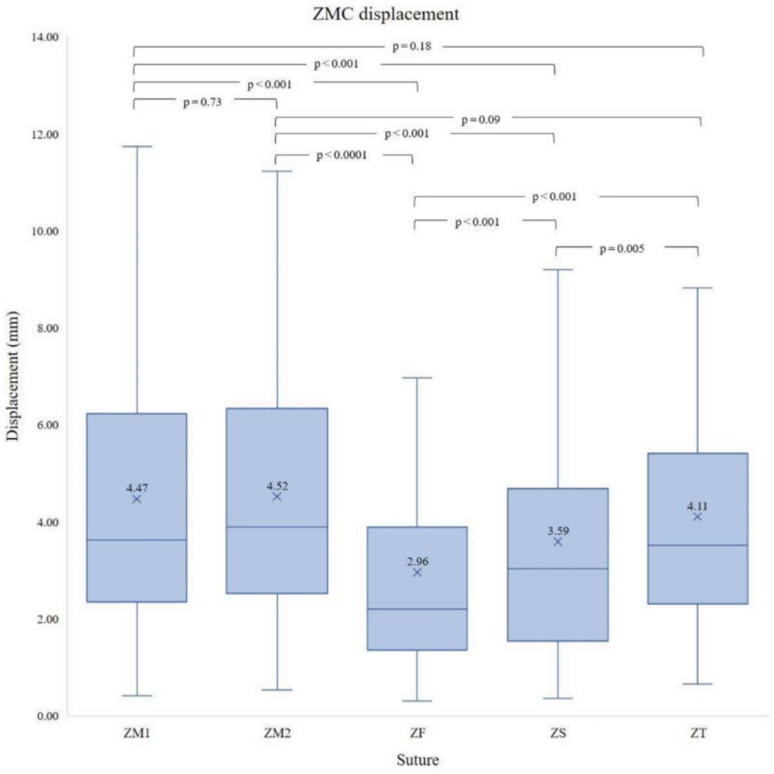

Fig. 4. Average displacement of the five ZMC sutures.

Multivariate logistic regression to identify predictors for postoperative complications showed that the total displacement score increased the rates of facial complications ($P = 0.01$) and reoperation ($P = 0.02$) but was not a significant predictor of orbital complications ($P = 0.45$). Degree of rotation along the lateral-medial axis demonstrated a similar pattern (Table 2). All other suture displacement distances, rotational directions, and rotational distances were insignificant.

DISCUSSION

Our study analyzed unilateral ZMC fractures using 3D imaging to determine displacement distances at the five articulations of the zygoma in addition to the common rotational patterns and distances. This method utilized the mirrored, intact ZMC to represent the "normal" position of the zygoma under the assumption that zygomas have relative symmetry.[11,12]

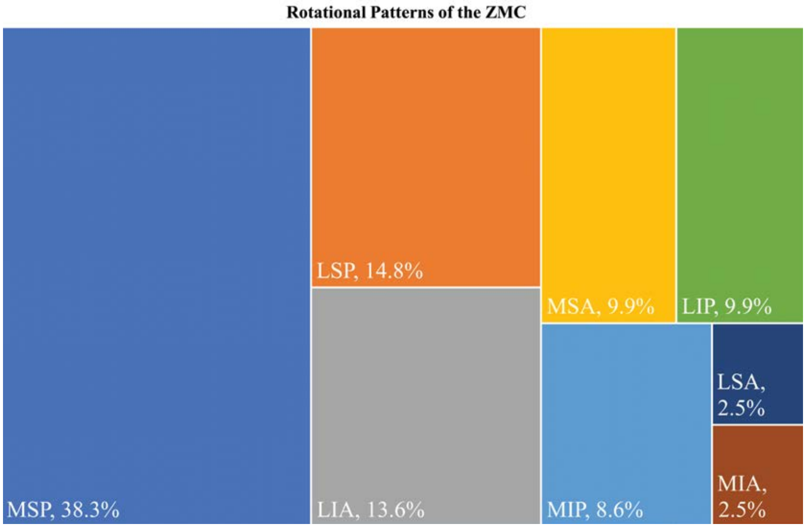

Fig. 5. Most common rotational patterns of the ZMC. A: anterior, P: posterior, S: superior, I: inferior, L: lateral, and M: medial.

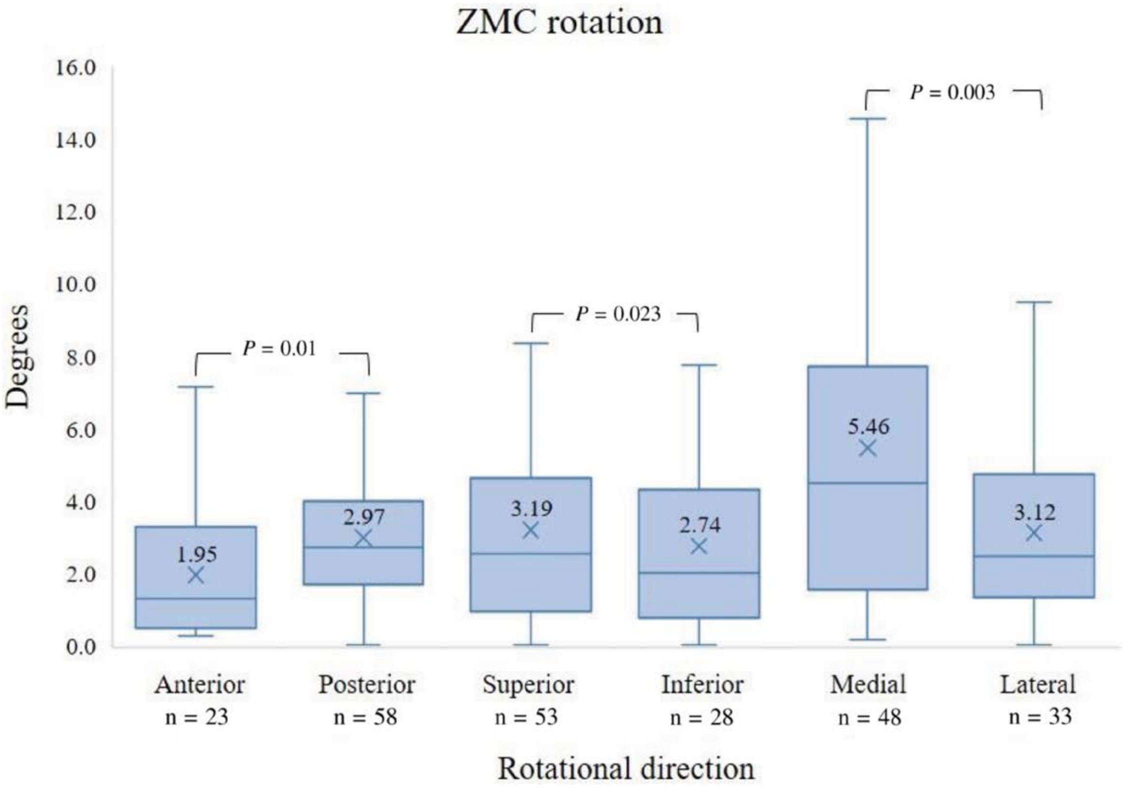

Fig. 6. Rotational direction and degree of rotation of the zygoma body along each axis.

The majority of our patients presented secondarily to injury mechanisms that would have likely dealt anterior (motor vehicle accident) or lateral forces (assault). Intuitively, these forces would translate to dislocation primarily along the lateral-medial axis, with some movement along the anterior-posterior axis. The data support this notion with the ZM1 and ZM2 experiencing the greatest displacement. Both articulations would absorb the highest force from an anterior blow to the midface. Similarly, the ZT saw significantly more displacement than the ZF as one would expect from a lateral blow. The most common rotational pattern—posterior, superior, and medial—would be suspected in an anterior or lateral blow. This pattern of injury represents an inward, "crush" force with upward velocity as would be expected from an airbag deployment, fall, or blunt trauma.

Anytime the zygoma experiences a force, the zygoma will be rotated along the lateral-medial, superior-inferior, and anterior-posterior axes. In our patient population, the most prevalent mechanism of injury was a motor vehicle accident resulting in significantly greater rotation along the lateral-medial axis. Interestingly, prior studies of zygoma rotation using 3D analytics found similar results despite patients presenting most commonly from falls and blunt trauma.[9,10] These findings suggest that perhaps the zygoma has a structural predilection toward being rotated along the lateral-medial axis. To further elucidate this relationship, intra-axis analysis showed the zygoma rotated the greatest medially and rotated the least anteriorly. For increased medial rotation, there would have to be significant fracturing at the ZM1 with possible fracturing of the ZM2 and ZT. In contrast, to have anterior rotation, there should be a higher degree of displacement at the ZF. Additionally, the ZM1, ZM2, and ZT are relatively thin sutures with minimal bony support, whereas the ZF and ZS are bolstered by the frontal and sphenoid bone, respectively. From a biomechanical standpoint, these findings are consistent with studies showing that the ZM1 and ZT experience significantly greater deformation compared with the ZF when experiencing an anterior-posterior force.[13,14]

Table 2. Multivariate Logistic Regression for Complications Predicted by Fracture Classification Systems*

	Orbital Complications			Facial Complications			Reoperation		
	Adjusted OR	95% CI	*P*	Adjusted OR	95% CI	*P*	Adjusted OR	95% CI	*P*
Total displacement score	1.02	(0.96–1.09)	0.45	1.11	(1.03–1.22)	0.01	1.08	(1.02–1.17)	0.02
Lateral-medial axis rotational distance (degrees)	0.96	(0.78–1.15)	0.68	1.36	(1.12–1.75)	0.005	1.22	(1.02–1.48)	0.04

*Demographic and clinical variables that were entered into multivariate regression were age, time to operation, preoperative symptoms, and choice of approach to the infraorbital rim/orbital floor.

CI, confidence interval; OR, odds ratio.

The decision to undergo surgical correction of a ZMC fracture can be difficult as the factors that indicate open reduction and internal fixation (ORIF) are often times unclear.[15,16] One study suggested that a nondisplaced fracture may be treated with a conservative approach, whereas depressed fractures require surgical intervention.[17] Another retrospective review of maxillary fractures illustrated that 78% of ZMC fractures were managed nonoperatively, with the other 22% undergoing ORIF.[18] In general, the decision to operate is focused on aesthetic and functional improvement.[19] If ZMC trauma is viewed on a spectrum based on severity, the extremes (no displacement and severe displacement/comminution) may be managed nonoperatively and operatively, respectively. However, evaluating the need for surgical intervention for the ZMC fractures that fall in the middle of the spectrum can be subjective and inconsistent. Our multivariate analysis for clinical outcomes shows that patients with higher total displacement scores had higher rates of facial complications and reoperations. As such, this method could be utilized to calculate a total displacement score to provide a quantitative measure to support clinical findings in evaluating which ZMC fractures would benefit from ORIF.

Our study demonstrated that rotational distance along the lateral-medial axis was significantly associated with facial complications and need for reoperation. Similarly, Pau et al found that patients with severe displacement along the lateral-medial axis had higher rates of ORIF.[9] Rotational distances along the superior-inferior and anterior-posterior axis were not significantly associated with any complications or reoperation on multivariate analysis. One could theorize that patients who experienced complications despite ORIF could potentially have worse outcomes if treated nonoperatively. As such, surgeons should pay particularly close attention to lateral-medial rotation of the zygoma during preoperative evaluation and have a low threshold for surgical intervention. Theoretically, one would also expect that lateral-medial rotation would be significantly associated with orbital complications. Rotation along the lateral-medial axis would increase or decrease intraorbital volume by disrupting the orbital floor, thus making surgical correction increasingly difficult.[20,21]

There have been two prior studies analyzing ZMC fractures using 3D renderings to measure rotation.[9,10] However, the applications of these studies were limited in that they did not compare fracture patterns with patient outcomes, displacement and rotations were manually measured, and they reported relatively small sample sizes.[9,10] Manual alignment and rotation can be highly subjective, and the rotation order applied can influence the obtained values. Our study sought to reduce potential user error by automating the measurement process and tracking patient outcomes with a larger sample size to increase clinical applicability. Additionally, the most common mechanism of injury in the studies by Pau et al and Toriumi et al were blunt trauma or falls[9,10]; the majority of patients in our study presented secondary to motor vehicle accidents. Common injury mechanisms vary by region and we would posit that our data would be more applicable to regions with higher rates of commuting: for example, regions with less urban density.

As with all retrospective studies, there are several limitations to this study. Although this study validates a relatively objective method of measuring zygoma displacement and rotation, implementing this method in daily practice may be challenging. Learning the software and the time needed to segment the zygoma can be time-intensive and costly. Granted, there is typically a latency period between injury and surgery,[15,22] which may allow for application of this method as part of the surgical plan. Nonetheless, previously established ZMC classification schemata[4,8] may be more clinically applicable. In terms of objectivity, our method falls short of being completely objective, as the predefined suture points and zygomatic body selection is a user-selected process. To limit these discrepancies, a single user defined the areas of interest, and all calculations of displacement and rotation were automated. Further studies utilizing a nonoperative group for comparison could provide additional data to determine which patients warrant surgical intervention.

CONCLUSIONS

Any traumatic force to the midface can disrupt and rotate the ZMC. Our study attempted to quantify these changes by utilizing an automated method to calculate displacement, rotational pattern, and degrees rotated. The data demonstrated that the ZM1, ZM2, and ZT experienced greater displacement relative to the ZF, and that the most common rotational pattern was medially-superiorly-posteriorly. With higher total displacement scores and increased degrees rotated along the lateral-medial axis, patients had higher rates of postoperative complications and reoperations. These findings can be used to better understand how traumatic insults affect the ZMC and underscore that certain rotations and displacements can have clinical implications.

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