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Original Article

Symmetry recovery in zygomaticomaxillary complex fractures compared to normal unfractured population: A new reliable 3D evaluation

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ABSTRACT

Objective: This study aims to quantify the facial symmetry of surgically treated zygomaticomaxillary complex (ZMC) fractures through a new reliable three-dimensional evaluation method, which is crucial for improving post-operative aesthetic and functional outcomes.
Material and methods: Healthy patients and patients with surgically treated ZMC fractures were retrospectively reviewed. Using Brainlab Elements® the zygomatic bone and the orbit of each patient was segmented and mirrored. Subsequently, the mirrored side was matched with the other side via volume-based registration, using the segmented orbit as reference. Volumetric asymmetry was measured using 3-matic software, and a surface-based matching technique was used to calculate the mean absolute differences (MAD) between the surfaces of the two sides of the ZMC. The reliability of this novel method using volume-based registration was tested, and the intra-class correlation coefficient was assessed.
Results: The MAD between the surfaces of the left and right sides in the control group was 0.51 mm (±0.09). As for the ZMC fracture group, MAD was 0.78 mm (±0.20) and 0.72 mm (±0.15) pre- and post-operatively, respectively. The MAD showed statistically significant differences between pre- and post-operative groups (p = 0.005) and between control and post-operative groups ($p < 0.001$). The intra-class correlation coefficient was high (≥0.99).
Conclusions: This evaluation method using mirroring and volume-based registration to determine the symmetrical position of the ZMC is reliable. The surface-based measurements revealed an improved symmetry after surgery. However, the symmetry of the treated patients remained lower than the control group.

1. Introduction

Fractures in the zygomatic bone region are common traumatisms due to the prominent convexity and orientation of the bones within the face [1,2]. Fractures of the zygomaticomaxillary complex (ZMC) can result in facial asymmetry, and even small displacements can result in significant functional and aesthetic deformities [3]. The aesthetic aspect of the face is shaped by both hard and overlying soft tissues and impacts facial symmetry. A symmetrical hard tissue base is considered indispensable for a symmetrical face [4]. Facial asymmetry can cause psychological problems, resulting in a lower quality of life [5]. Visual zygomatic symmetry is mainly determined by the malar eminences [6,7]. Consequently, it is essential for surgical reduction and fixation of a ZMC fracture to ensure the correct horizontal and vertical position for optimal facial symmetry and function [4]. Therefore, it is important to address this issue and consider symmetry in treatment planning.

Geometric morphometric measurements with three-dimensional (3D) computed tomography (CT) scans and Computer Aided Design (CAD) tools can aid in the accurate treatment planning of surgical reconstruction and further post-operative evaluation of treatment outcomes [8−12]. Facial symmetry after the surgical treatment of fractures can be assessed in different ways. The outcome is usually observed clinically and by radiographic imaging, whereas the visualization of the osseous ZMC is best attained with CT or cone beam CT (CBCT) scans [5,7,13,14]. Objectively, symmetry can be assessed using cephalometry, landmark-based registration, surface-based registration, or voxel-based registration [4,6-13,15-24]. In existing literature, there are some methods for the quantitative assessment of ZMC symmetry on CT; however, they are based on linear distance or angle measurements, and thus, asymmetry is quantified by a few

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landmarks within the CT slides. An analysis of the entire ZMC surface is found superior for measuring its symmetry [13,15,25]. Some studies that describe this method use areas adjacent to the ZMC or the ZMC surface itself, and therefore, they do not consider the position of the ZMC within the viscerocranium [13,15,25]. One study considered the position of the ZMC within the viscerocranium using the anterior cranial fossa as a reference [26]. However, this method underestimated the ZMC symmetry, as the distance from a point on the ZMC to the corresponding point on the mirrored ZMC surface is often larger than the distance to the closest point on the mirrored ZMC surface. Moreover, the asymmetry of the anterior cranial fossa was not considered [26].

The aim of this study is to quantify the facial symmetry of surgically treated ZMC fractures through a reliable three-dimensional (3D) evaluation method using the segmented orbit as a reference for the reconstruction of the zygomatic bone, and to compare this analysis to a control group.

2. Material and methods

2.1. Ethical approval

This research was conducted in compliance with the principles of the World Medical Association Declaration of Helsinki on medical research and all applicable regulatory requirements. The study protocol was approved by the Ethics Committee of the Catholic University and Hospital of Leuven (MP016783).

2.2. Study patients

All patients with unilateral ZMC fractures, classified as type B following Zingg classification (Fig. 1), surgically treated between January 2014 and December 2020 with pre- and post-operative scans were included in the study. Only CT or CBCT scans were used with a slice thickness of 0.4−1 mm and a field of view where the complete maxillary complex and the orbital roof were included. Zingg type B fractures are classic tetrapod fractures [2]. All patients were treated in the conventional method, that is, through intraoperative reduction and fixation without using navigation or intraoperative imaging. The exclusion criteria were patients with panfacial fractures, bilateral fractures, Le Fort II and Le Fort III fractures, isolated blow-out fractures of the orbital floor, and diagnosis of congenital craniofacial syndromes. Additionally, patients with immediate loss of follow-up were excluded. The patients' records were reviewed for patient demographics, aetiology, type of fracture, volumetric analysis, and follow-up. A group of healthy patients without facial fractures were selected as the control group, with each patient having one CT scan of the maxillofacial complex available. The final study group after fulfilling the inclusion and exclusion criteria consisted of 74 patients, and the control group consisted of 100 patients.

2.3. 3D evaluation protocol

CT/CBCT images were exported as Digital Imaging and Communications in Medicine (DICOM) data files and imported into Brainlab Elements® (Brainlab AG, Munich, Germany) where the images were reoriented according to the Frankfurt horizontal plane. The orbit and the zygomatic bone were automatically segmented bilaterally with Brainlab Elements® (Brainlab). Then, the orbit and the zygomatic bone of each side were merged. The unfractured side was mirrored on the fractured side for the study group patients, while the left side was mirrored on the right side for the control group. To ensure correct overlapping, volume matching on the cranium, using the orbit volume as a reference, was applied between the fixed side and the mirrored side (Fig. 2). These two volumes were afterwards exported as Standard Tessellation Language (STL) files. The two exported STL files were imported into 3-matic (Materialise, Leuven, Belgium) to calculate the volumes of each side and the difference in distance between the surfaces of the two sides. This is also known as colour-coded distance map, which was represented as the mean absolute difference (MAD) in millimetre (Fig. 3).

2.4. Statistical analysis

Statistical analysis was performed using the statistical package SPSS (version 28.0.1.1) for Windows; SPSS, Inc. [21]. Descriptive analysis was reported as mean ± standard deviation (SD). Cross-tabulation and univariate logistic regression were used to evaluate

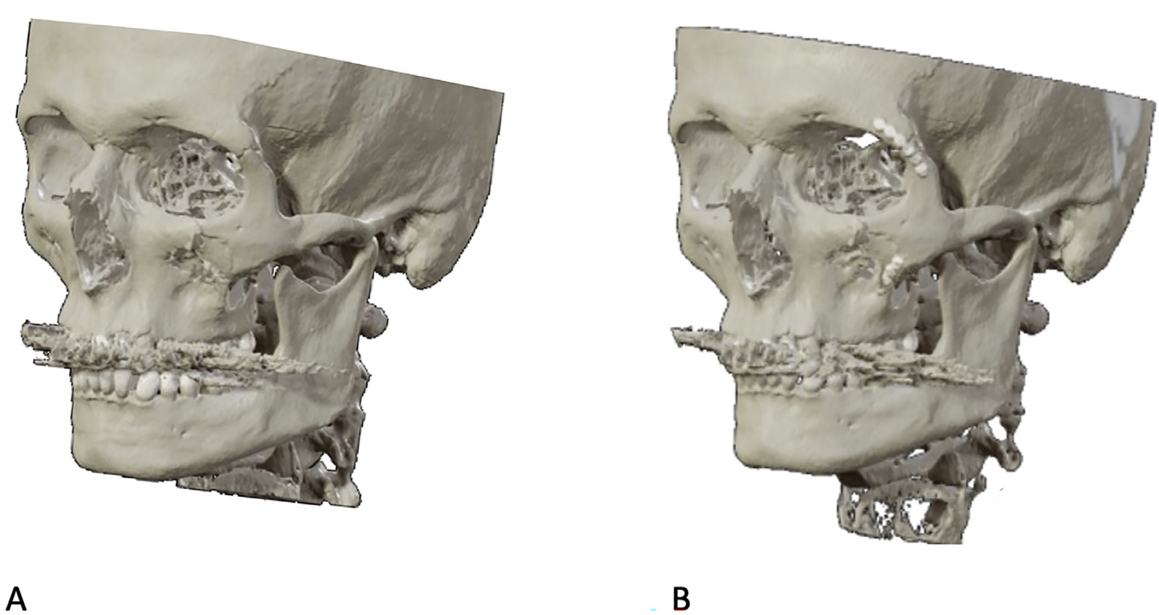

Fig. 1. 3D bone model in Brainlab Elements®. a) Patient with Zingg type B fracture. b) Same patient after 2-point fixation at the frontozygomatic suture with a KLS Martin 1.8 6-hole plate and six 1.8 × 5.0 mm micro screws and at the zygomaticomaxillary buttress with a KLS Martin 1.5 4-hole plate and four 1.5 × 5.0 mm micro screws.

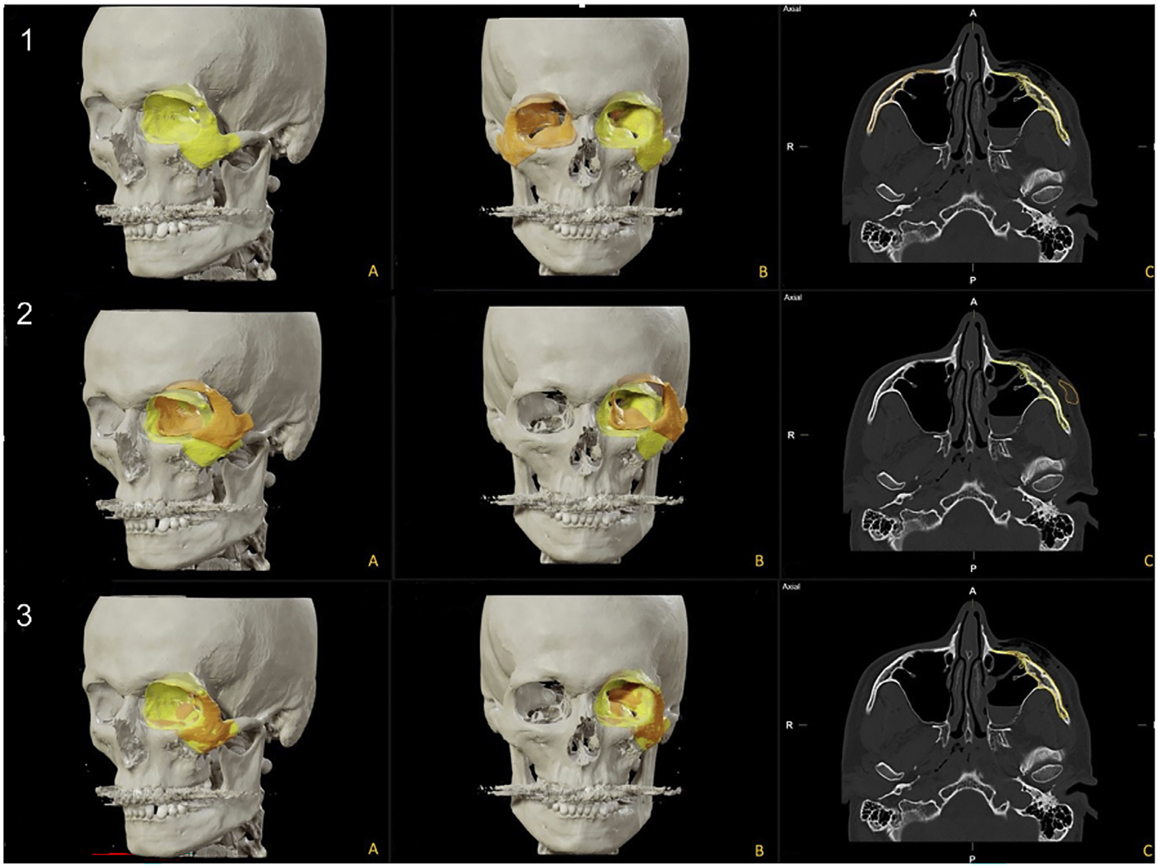

Fig. 2. Procedure of the 3D evaluation protocol in Brainlab Elements® (patient of Fig. 1).

1a-b) 3D segmented zygomatic bone and orbit using automatic segmentation (left is shown in yellow, right is shown in orange). 1c) Axial slice showing projection of segmented bone.

2a-b) 3D model after mirroring of unfractured side (right) onto fractured side (left). 2c) Axial slice showing projection of segmented bone after mirroring.

3a-b) 3D model after volume matching on the cranium, using the segmented orbit, to guarantee correct overlap. 3c) Axial slice showing projection of segmented bone after volume matching.

significant associations between explanatory variables and outcome. Quantitative data were compared between the groups using either the paired *t*-test or independent *t*-test, wherever appropriate. The χ^2 test was used to compare qualitative variables between the groups. Probabilities of less than 0.05 were statistically significant. To analyse the variability of the distance and volumetric measurements, intra- and inter-observer reliability were calculated using the intra-class correlation coefficient (ICC) test between the measures of two observers and repeated measures of both observers.

3. Results

The medical files of 74 patients with a type B ZMC fracture and 100 control patients were analysed. The patient characteristics are described in Table 1. Despite the gender and age difference between the two groups, analysis has shown that age does not have an influence on the volume difference between left and right sides in both men and women ($p > 0.05$). An analysis of inter- and intra-observer variability of the volumetric measures of the two observers showed excellent reliability (ICC $\geq$ 0.99).

The ratio (left/right) of the volumes of the ZMC in the control group was normally distributed, as shown in Fig. 4. The mean ($\pm$SD) ratio (left/right) of the volumes of control, pre- and post-operative groups was 1.05 ($\pm$0.05), 1.07 ($\pm$0.10), and 1.05 ($\pm$0.11) respectively. Volumetric and surface analysis of the control and study groups is described in Table 2 by subdividing the study group into pre- and post-operative subgroups. The mean ratio (left/right) of the ZMC was close, compared to the three groups, with no statistically significant difference between the groups. A strong correlation was found between the left and right volumes for the control group, followed by the post-operative group; it was slightly less for the pre-operative group. The MAD of the ZMC was the least for the control group, followed by the post-operative and pre-operative groups. The MAD between the ZMC in the control group was 0.51 mm ($\pm$0.09 mm). A statistically significant MAD difference was found between the control and post-operative ZMC fracture groups ($p < 0.001$) and a significant difference was found before and after treatment ($p = 0.005$).

Differences between genders of the control group are described in Table 3. Statistically significant differences of left ZMC volume ($p < 0.001$) and right ZMC volume ($p < 0.001$) were found between males and females, which correspond to significantly higher volumes of both left and right ZMC in males. Females appeared to have statistically less significant mean absolute differences than males ($p = 0.005$). The volume in men is slightly larger, and the variation is also slightly larger. The intra-individual variation in men, left and right, is 0.479 cm^3. For women, the intra-individual difference is 0.394 cm^3. This is a variation of 0.085 cm^3, which is clinically not relevant.

4. Discussion

A symmetrical analysis of the hard tissue of the ZMC can be used for diagnosis, treatment planning, and treatment outcome evaluation [5,18]. Accordingly, different methods to objectify facial symmetry have been discussed in existing literature, but there is a lack of consensus and consistency [8–12]. The shape or volume of the ZMC and

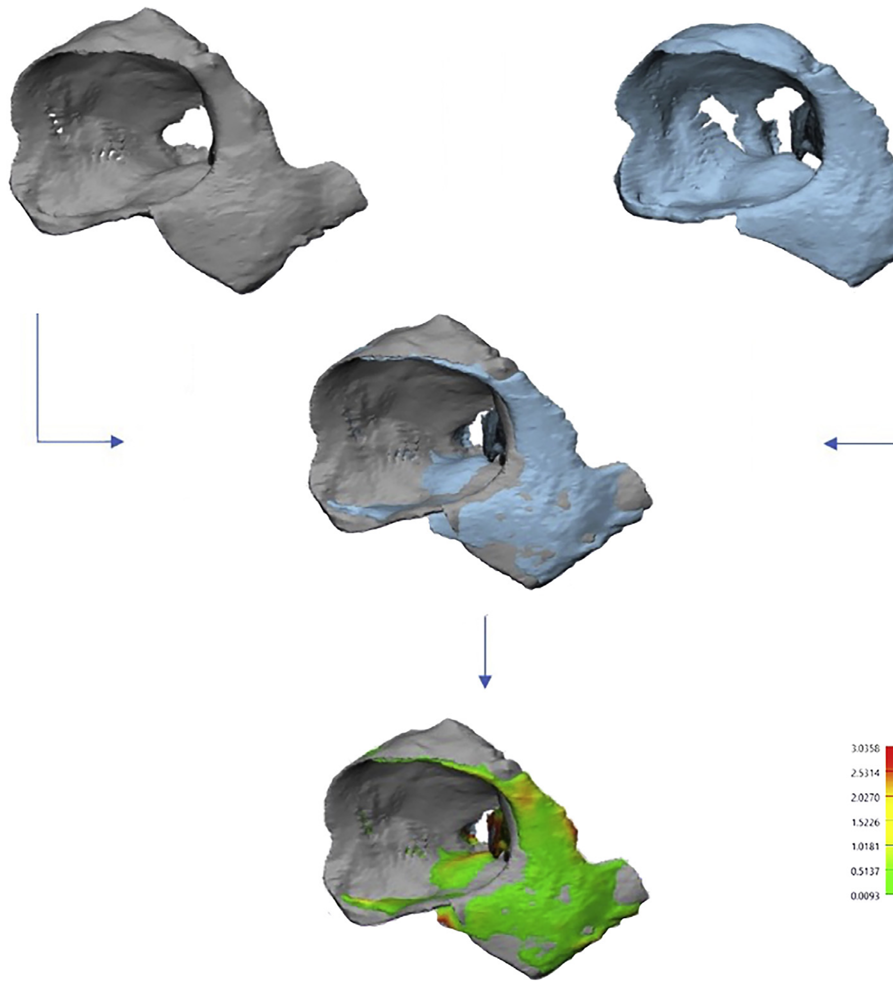

Fig. 3. Procedure of the 3D evaluation protocol in 3-Matic software (patient of Fig. 1). A) STL of 3D fractured side (grey) B) STL of mirrored and superimposed unfractured side (blue). C) Superimposition of unfractured and fractured side D) Colour coded distance map representing absolute differences (AD) in mm between the surfaces of the fractured and the unfractured side. Red areas representing large AD, orange representing intermediate AD and green representing small AD. In this case with a range of 0.01−3.04 mm and mean AD of 0.66 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

its 3D position defines the cheek projection in the face. Therefore, the position of the ZMC within the viscerocranium is a key factor in facial symmetry and appearance. Consequently, in this study, a new 3D evaluation method using volume matching was applied to assess the symmetry of ZMC patients, and it was compared to a normal population. To ensure correct overlapping, volume matching on the cranium was applied using the orbit volume as a reference. The calculated ICC was ≥0.99, implying that this method is easy and reliable.

Measurements consisted of volumetric comparisons between the left and right sides of the ZMC in terms of ratios (left/right) in case of the control group and between fractured and unfractured sides in case of the study group for both pre- and post-operative subgroups.

Table 1
Patient characteristics of the study and control groups in terms of mean ± standard deviation (±SD), and cross-tabulation for the control group and the study group.

	Control group (n = 100)	Study group (n = 74)	p-value
Gender			0.009
Male	36 (36.0 %)	42 (56.8 %)	
Female	64 (64.0 %)	32 (43.2 %)	
Age (years)	25.0 (±12.1)	44.8 (±18.5)	< 0.001
Range (years)	14.6−66.5	14.3−93.4	
Postoperative follow-up (months)	−	4.8 (±5.8)	

Surface-based measurements described as mean absolute difference (MAD) were also applied between the two sides. Using the control group (100 healthy cases) as reference, no significant difference in ratios (left/right) was found between the groups. However, a difference in MAD (p = 0.005) was found between the pre- and post-operative subgroups and between the control group and post-operative subgroup (p < 0.001). A strong correlation between the left and right ZMC volumes was found in the three different groups. Furthermore, the MAD values in this study were in line with previous studies, with a MAD ranging from 0.1 to 1.4 mm [13,15-17].

The results confirm the effect of surgical treatment on facial symmetry as MAD decreases significantly after surgery, and the ratio improves. Treating ZMC fractures involves reducing and fixating the zygomatic bone in the correct position. This generally does not involve adding or removing bones and thus changing volume. However, the reconstruction of the zygomatic bone will show better alignment, which allows for better segmentation. The projection and shape of the fractured side resembles the unfractured side post-operatively, resulting in a lower MAD, which is in accordance with the healthy control group. Furthermore, the correlation between the left and right volumes also improves after surgery, which indicates greater similitude after treatment. In conformation with current evidence in existing literature, 3D virtual planning and intraoperative navigation improve fracture reduction regarding displacement and symmetry [27]. However, in this study, symmetry and correlation

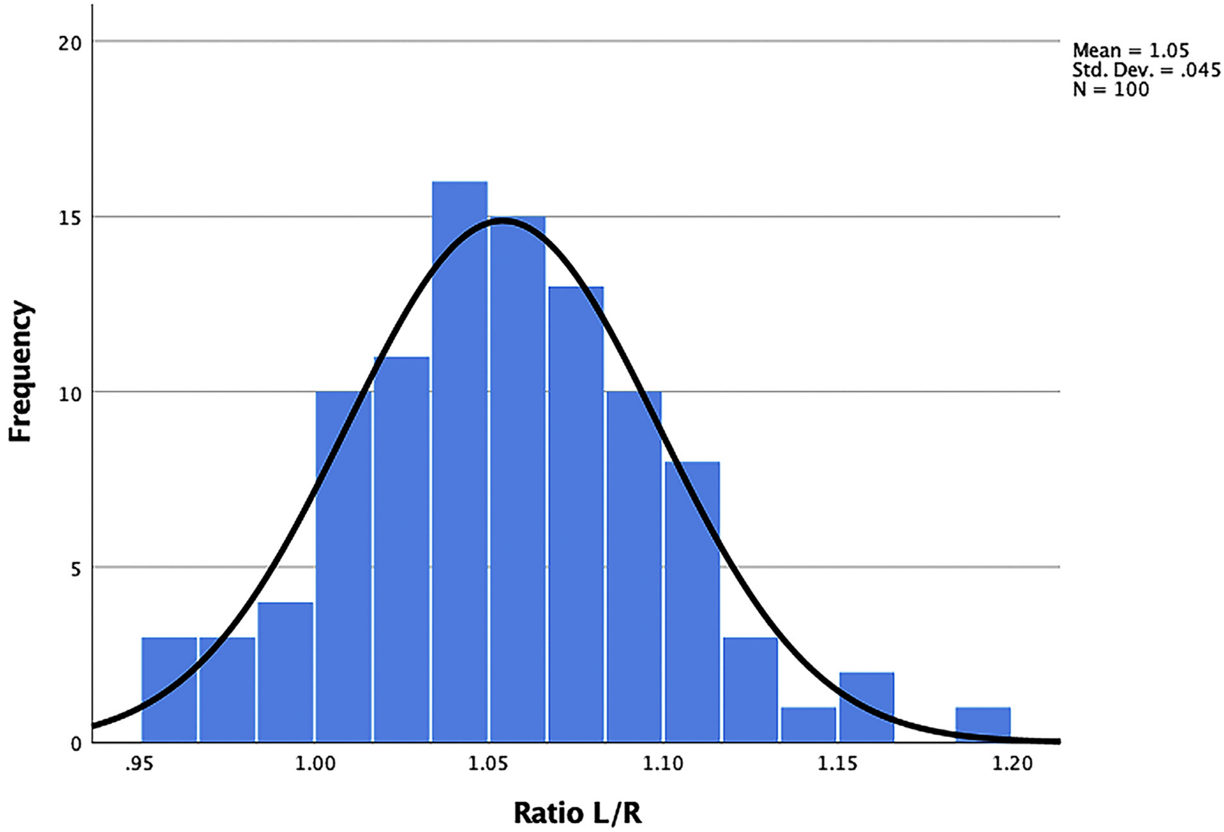

Fig. 4. Distribution of Left/Right (L/R) ratio of the control group (n = 100 patients).

Table 2
Volumetric and surface analysis of control and study groups.

	Control (n = 100)	Pre-operative (n = 74)	Post-operative (n = 74)	p-value*	p-value**
Volume ratio (L/R)	1.05 (±0.05)	1.07 (±0.10)	1.05 (±0.11)	p = 0.33	p = 0.07
Left ZMC volume (cm^3)	10.4 (±1.7)	11.6 (±2.0)	12.7 (±2.6)		
Right ZMC volume (cm^3)	9.9 (±1.8)	11.0 (±2.3)	12.3 (±3.0)		
Correlation left and right	0.97	0.89	0.92		
Mean absolute difference (MAD) (mm)	0.51 (±0.09)	0.78 (±0.20)	0.72 (±0.15)	p < 0.001	p = 0.005

* Difference between control and pre-operative group.
** Difference between pre-operative and post-operative group.

between left and right volumes of treated patients were still lower compared to those of the control group, indicating that patients still show a degree of asymmetry post-operatively when set side-by-side with the control group.

Prior studies have investigated facial symmetry based on two-dimensional (2D) images using cephalometric measurements [7,23,24]. However, the projection of 3D objects on 2D images can cause the superimposition of different anatomical parts, loss of anatomical details, indistinct anatomical replication and distortion [21]. Several methods to objectify facial symmetry with 3D data have been reported in existing literature. Manual measurement of points or landmarks can be used to evaluate facial symmetry, but these methods are prone to human error, a higher inter-observer variability, and subsequently, an imprecise depiction of facial symmetry [4,6,19,22]. More automated techniques using structural segmentation followed by mirroring and/or superimposition, based on surface or volume, have already been investigated [8-13,15-18]. Surface-based registration, which is based on contouring, is reported as less accurate because it is prone to rendering errors of 3D cortical surfaces and is observer-dependent compared to voxel-based registration [9–12]. It is claimed that voxel-based registration, which is based on volumetric differences, is the gold standard, as it has the least variability [9–12]. In this study, the 3D evaluation protocol relied on automatic segmentation and voxel-based registration.

Table 3
Volumetric analysis and surface analysis of the control group represented as mean ± standard deviation (±SD).

	Males (n = 36)	Females (n = 64)	p-value
Volume ratio (L/R)	1.06 (±0.04)	1.049 (±0.47)	p = 0.08
Left ZMC volume (cm^3)	11.6 (±1.7)	9.8 (±1.5)	p < 0.001
Right ZMC volume (cm^3)	10.9 (±1.6)	9.4 (±1.6)	p < 0.001
Mean absolute difference (MAD) (mm)	0.74 (±0.17)	0.67 (±0.14)	p < 0.001

Even though the segmentation in Brainlab Elements® was automatic, it was noticed that the segmentation of the fractured side was slightly overestimated since the segmentation is atlas-based. Therefore, some cases had imperfect segmentation. Future software updates should refine segmentation to a higher quality. The asymmetry of the face is notably impacted by the overlying soft tissues. In the present study, only the symmetry of bone was evaluated, and even if the bone is perfectly symmetrical, patients can still complain about perceived asymmetry [28]. Thus, it can be concluded that further research should include both soft and hard tissue symmetry analysis.

5. Conclusion

The facial symmetry of surgically treated ZMC fracture patients was evaluated in 3D using mirroring and volume-based registration and compared to a healthy control group. Surface-based measurements revealed a significant decrease in MAD after surgery, indicating an improved symmetric effect of the surgery compared to that pre-operatively. Although, the facial symmetry of the treated patients was still lower than that of the control group, the currently proposed evaluation method has been proven as easy and reliable. Moreover, it considers the shape and volume of the fractured ZMC, using volume matching of the mirrored and segmented healthy side, within its relation to the viscerocranium.

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Ethical approval

Ethical approval obtained from the Ethical Review Board of the University Hospitals Leuven (reference number: MP016783).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

K. Dubron: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **L.H. Yang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **R. Jacobs:** Writing – review & editing, Validation, Supervision, Software, Conceptualization, Data curation, Project administration, Resources. **C. Politis:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R. Willaert:** Project administration, Data curation, Conceptualization, Resources, Software, Supervision, Validation, Writing – review & editing. **E. Shaheen:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing.

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