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ORIGINAL ARTICLE

Three-dimensional quantification of skeletal midfacial complex symmetry

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Abstract

Purpose Quantification of skeletal symmetry in a healthy population could have a strong impact on the reconstructive surgical procedures where mirroring of the contralateral healthy side acts as a clinical reference for the restoration of unilateral defects. Hence, the aim of this study was to three-dimensionally assess the symmetry of skeletal midfacial complex in skeletal class I patients.

Methods A sample of 100 cone beam computed tomography (CBCT) scans (50 males, 50 females; age range: 19–40 years) were recruited. Automated segmentation of the skeletal midfacial complex was performed to create a three-dimensional (3D) virtual model using a convolutional neural network (CNN)-based segmentation tool. Thereafter, the segmented model was mirrored and registered to quantify skeletal symmetry using a color-coded conformance mapping based on a surface part comparison analysis.

Results Overall, the mean and root-mean-square (RMS) differences between complete true and mirrored models were 0.14 ± 0.12 and 0.87 ± 0.21 mm, respectively. Female patients had a significantly more symmetrical midfacial complex (mean difference: 0.11 ± 0.1 mm, RMS: 0.81 ± 0.17 mm) compared to male patients (mean difference: 0.16 ± 0.13 mm, RMS: 0.94 ± 0.23 mm). No significant difference existed between left and right sides irrespective of the patient's gender.

Conclusion The comparison between true and mirrored complete and left/right split midfacial complex showed symmetry within a clinically acceptable range of 1 mm, which justifies the applicability of using the mirroring technique. The presented data could act as a reference guide for surgeons during planning of reconstructive surgical procedures and outcome assessment at follow-up.

Keyword Midfacial complex · Symmetry · Automatic segmentation · CBCT · Mirroring reconstructive surgeries · Virtual surgical planning

Introduction

Midfacial complex refers to the middle portion of the osseous facial architecture which significantly contributes toward defining the facial form. It incorporates maxilla, nasal skeleton, orbital rim, and zygoma (including the entire length of zygomatic arches), which are bounded by frontomaxillary, frontozygomatic and frontonasal suture lines. The clinical relevance of the midfacial complex cannot be ignored as it is one of the most commonly fractured regions requiring surgical correction, accounting for approximately 60% of all maxillofacial fractures [1–3]. Furthermore, midfacial complex deformity correction is often performed through reconstructive surgery for improving facial esthetics and functionality. One of the main required outcomes of these surgical interventions is the restoration of facial symmetry following functional recovery.

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With the advent of three-dimensional (3D) computed tomography (CT)/cone beam CT (CBCT) imaging, surface-based skeletal symmetry evaluation techniques have been widely applied for diagnostics, reconstructing symmetrical facial skeletal structures, and outcome assessment [4–7]. These 3D methodologies have replaced the conventional landmark-based assessment techniques [8, 9] which make the morphological assessment problematic owing to a high degree of human error, observer variability and high time consumption [10]. In addition, the main steps involved in the 3D symmetry evaluation and virtual surgical planning for achieving a symmetrical skeletal outcome in patients with defects consist of surface segmentation followed by mirroring and superimposition of the normal region onto the defected side [11–13]. These steps have been employed for quantifying symmetry of orbital [14, 15] and zygomatic bone [16, 17] in a healthy population for the purpose of providing a reference benchmark which facilitates the surgical reconstruction of skeletal defects.

The most vital step for symmetry assessment involves segmentation or skeletal surface reconstruction for the creation of a virtual 3D model from CT/CBCT datasets. Any flaw in this step would contribute toward accumulation of error in the later steps. Studies assessing symmetry of skeletal structures rely mainly on semi-automatic segmentation software programs which are prone to certain limitations, such as threshold selection, observer variability and over- or under-segmentation requiring time-consuming manual intervention [18–20], which in turn could lead to an inaccurate symmetry assessment. To overcome these limitations, convolutional neural network (CNN)-based deep learning algorithms have been applied for automated segmentation of dentomaxillofacial structures from CBCT images and have shown promising results [21–23]. However, these artificial intelligence-based models still need to be applied for assessing symmetry of skeletal structures.

To our knowledge, limited evidence exists quantifying the midfacial complex symmetry in a healthy population group. Furthermore, no protocol exists quantifying skeletal symmetry with the application of CNN-based segmentation approaches [10]. Therefore, the following study was conducted to quantify the symmetry of midfacial complex on CBCT images of skeletal class I patients using a recently validated CNN-based automated segmentation tool [24], which could act as a reference guide for mirroring reconstructive surgical procedures in patients with skeletal defects and asymmetry. The hypothesis behind this work was that the automation of the segmentation step and provision of midfacial complex symmetry data would enhance the precision and time-efficiency of the symmetry evaluation process for further clinical applicability in patients requiring mirroring for reconstructive surgery.

Methods

This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research. Ethical approval was obtained from the Ethical Review Board of the University Hospitals Leuven (reference number: S57587).

Data collection

The sample size was calculated based on previous comparable studies [11, 14] using a priori power analysis in G*power software (version 3.1.9.4, University of Dusseldorf, Dusseldorf, Germany) at a power of 80% and 0.05 level of significance.

A total sample of 100 CBCT scans (50 males and 50 females) were recruited during the period 2018–2020, from the radiological database of UZ Leuven Hospital, Leuven, Belgium. The scans were acquired with NewTom VGi evo CBCT device (NewTom, Verona, Italy) using a standardized scanning protocol (field of view: 24 × 19 cm, voxel size: 0.3 mm). The inclusion criteria were adult healthy patients aged 19–40 years with skeletal class I who underwent CBCT scanning for justified dental or maxillofacial indications. Patients with a history of maxillofacial trauma, odontological surgical interventions, reconstructive surgery, existing pathology and skeletal deformity were excluded. All scans were saved in Digital Imaging and Communication in Medicine (DICOM) format for further processing.

Symmetry assessment protocol

Automatic segmentation

The segmentation of the skeletal midfacial complex was performed using a previously developed and validated CNN-based online cloud tool [24] known as the 'Virtual Patient Creator' (ReLu BV, Leuven, Belgium, Version October 2021). The DICOM images were uploaded to the tool which allowed automatic segmentation and generation of a virtual 3D model in Standard Tessellation Language (STL) file format. The segmented midfacial complex involved palatine, maxillary, zygomatic, nasal and lacrimal bones. The complex was bounded superiorly by replicating a Le Fort III fracture line which passed through frontonasal suture, frontomaxillary suture, orbital wall and frontozygomatic suture [25, 26]. Laterally and posteroinferiorly, it was limited till zygomaticotemporal and pterygomaxillary suture lines, respectively. Inferiorly, the complex extended up to the alveolar bone level. The teeth were automatically excluded from the segmented region as the CNN-based tool had been manually trained to specifically segment the skeletal complex and crop the dentition from the final segmentation output [24] (Fig. 1).

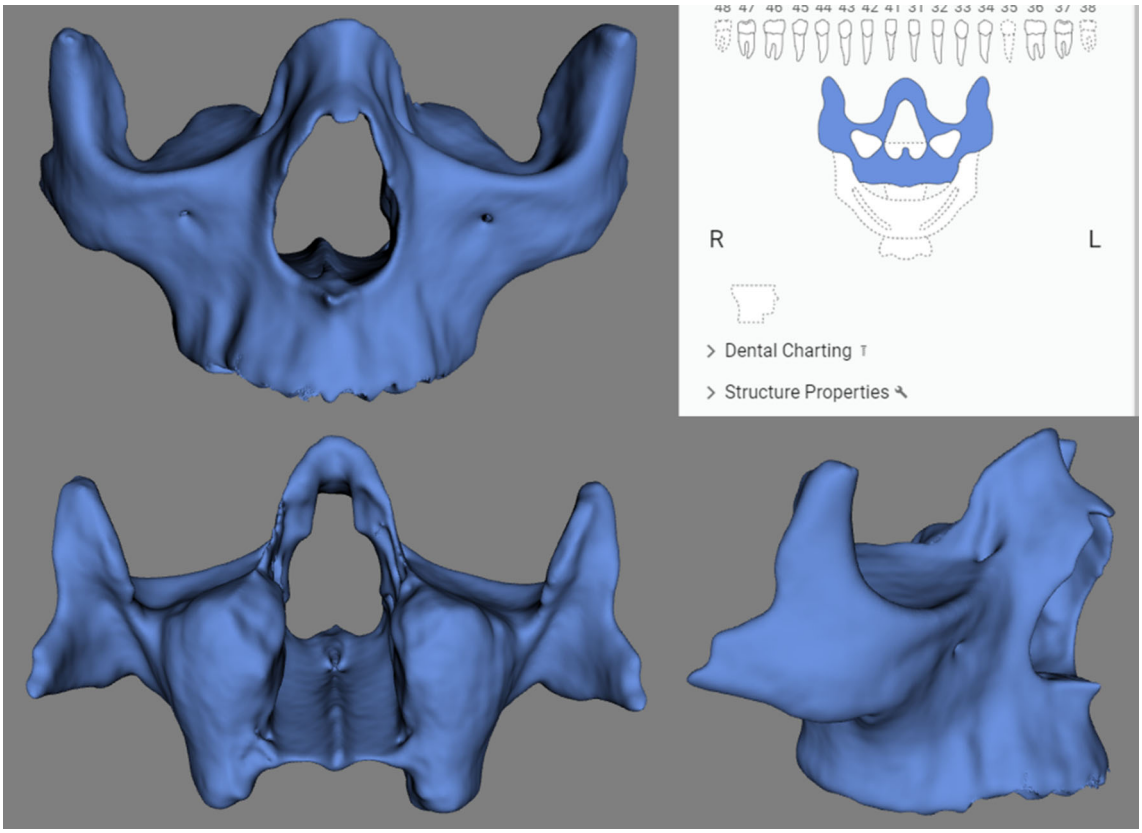

Fig. 1 Automatic segmentation of midfacial complex which include palatine, maxillary, zygomatic, nasal, and lacrimal bones, extending till the zygomaticotemporal, zygomaticofrontal, pterygomaxillary, pterygopalatine, frontomaxillary and frontonasal sutures

Later, the STL files of the midfacial complex were imported into Mimics Innovation Suite (version 23.0, Materialise N.V., Leuven, Belgium) to confirm the visual quality of the segmentation. Visual inspection of the segmentation was performed by assessing the boundaries of the segmented midfacial complex overlapped onto the coronal, axial, and sagittal orthogonal planes of the CBCT images. If any minor discrepancy existed within the final segmentation, it was corrected manually using the 3D tools tab.

Mirroring and registration

Mirroring and registration were applied to quantify both the complete and unilateral left/right midfacial complex skeletal symmetry. The reasoning for that was to estimate the range of normal symmetry, which could act as an intuitive guide during the preoperative surgical planning phase and for analyzing residual postoperative asymmetry depending on the type of midfacial reconstructive surgery, i.e., either complete midfacial complex reconstruction or in cases where normal contralateral side acts as a reference.

Firstly, the STL files of automated segmentation were imported into 3-matic software (version 15.0, Materialise N.V., Leuven, Belgium), where a mirrored model of the complete midfacial complex was created by a "mirror" command using an arbitrary midsagittal plane which was automatically determined by the software (Fig. 2a). Thereafter, the mirrored model was registered onto the true model according to the least point-to-point distance between the two overlapped surfaces. This process was performed by applying global co-registration with enough iterations until the mean point-to-point distance for all point pairs reached their least value without any visible spatial changes (Fig. 2b). The registration distance threshold was set at 10 mm for a gross overlap and was gradually changed up to 0.5 mm for fine tuning the final registration and maximizing the conformance. Thereafter, morphological symmetry between the true and mirrored models was assessed using a color-coded conformance mapping based on the part comparison function. This allowed quantitative calculation of the difference between true and mirrored midfacial complexes, depending on the degree of conformity or variation between both sites. Figure 3 illustrates an example of a case showing color-coded part comparison analysis of a complete midfacial complex symmetry.

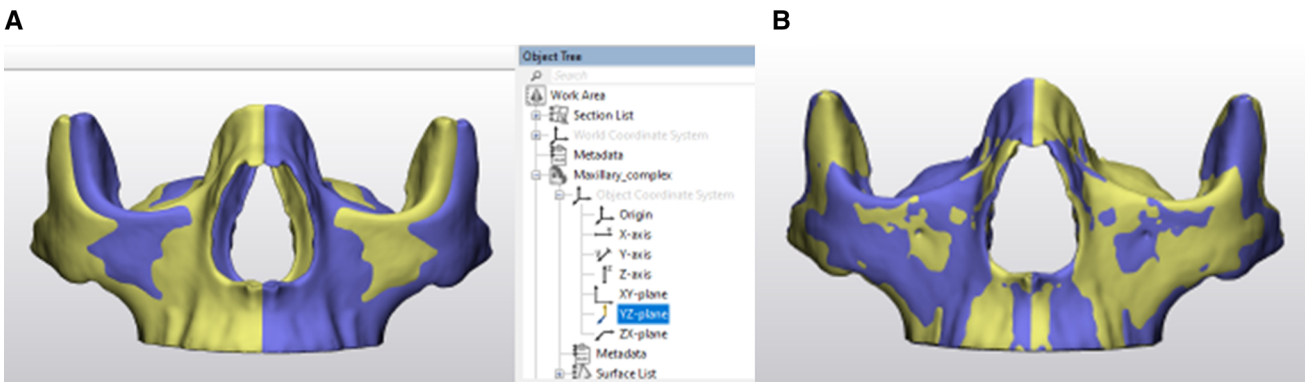

Fig. 2 Mirroring and registration steps of complete midfacial complex. A. Mirroring of midfacial complex based on an arbitrary midsagittal plane, B. Global registration of original and mirrored models

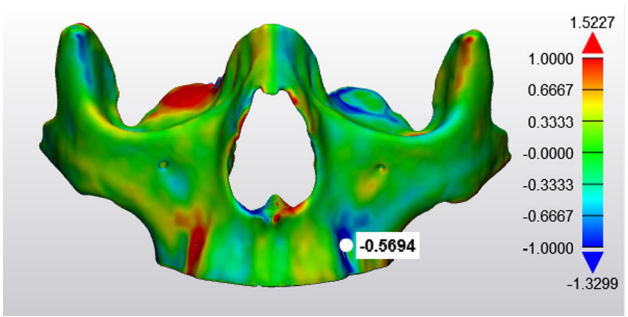

Fig. 3 Color-coded part comparison analysis between complete true and mirrored midfacial complex. Green color (zero value) corresponds to no difference between the true and mirrored overlapped models, deviation toward blue color (negative values) corresponds to under-estimation of true model, deviation toward red color (positive values) corresponds to over-estimation of true model

In addition, a mirror model of the left and right sides of the segmented complex was created using a midsagittal plane based on the following landmarks: posterior nasal spine, anterior nasal spine, and nasion. This plane has been found to be the most appropriate for assessing bilateral craniomaxillofacial symmetry [27, 28]. Each mirrored model was registered onto the opposing contralateral true model, i.e., the left mirrored model was registered onto the right true side and vice versa, followed by registration and part comparison as previously mentioned.

The entire procedure, starting from segmentation till part comparison, was performed blindly by two independent experts. Both observers repeated the assessment twice at an interval of 1 week for calculating intra- and inter-observer error and reliability.

Statistical analysis

Data were analyzed using IBM SPSS Statistics for Windows, version 21.0 (IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test was applied to assess the data for normal distribution and homoscedasticity was verified by conducting Levene's test. The symmetry was presented as the mean and root-mean-square (RMS) difference between the true and mirrored models of the complete and unilateral midfacial complex. A t test and two-way analysis of variance were applied for assessing the differences in symmetry of the complete and left/right split based on gender. The relative technical error of measurements (rTEM) was calculated for assessing the intra- and inter-observer error and classified into five categories (< 1% = excellent, 1–3.9% = very good, 4–6.9% = good, 7–9.9% = moderate, > 10% = poor) [29, 30]. Moreover, intra-class correlation coefficient (ICC) was applied at a 95% confidence interval for evaluating the inter- and intra-observer reliability (where < 0.50 = poor reliability; 0.50–0.75 = moderate reliability; 0.75–0.90 = good reliability; > 0.90 = excellent reliability) [31]. A p value of < 0.05 was considered as statistically significant.

Results

All data presented a normal distribution and exhibited homoscedasticity. The visual examination of the segmentations revealed that 20% of the automatic segmentations required manual corrections. However, the corrections were minor and clinically insignificant in nature. The rTEM for both intra- and inter-observer error ranged from good to excellent, where the least amount error was observed when mirroring a complete midfacial complex compared to split left/right sides. Moreover, inter- and intra-observer reliability revealed an excellent ICC value (> 0.99) for all parameters without any significant difference between observers (Table 1).

Table 2 describes the symmetry of the complete midfacial complex based on part comparison analysis. Overall, the mean and RMS difference between complete true and mirrored models were 0.14 ± 0.12 and 0.87 ± 0.21 mm,

Table 1 Intra- and inter-observer error and reliability of complete and unilateral left/right midfacial complex skeletal symmetry

		Complete true/mirrored		Right true/left mirrored		Left true/right mirrored	
		Mean	RMS	Mean	RMS	Mean	RMS
Intra-observer	rTEM	1.4%	0.18%	1.4%	0.24%	1.5%	0.35%
	ICC	0.999	0.999	0.999	0.999	0.998	0.999
Inter-observer	rTEM	1.8%	0.3%	5%	1.1%	6%	1.4%
	ICC	0.999	0.999	0.997	0.998	0.997	0.997

RMS: root-mean-square, rTEM: relative technical error measurements, ICC: Intra-class Correlation Coefficient

Table 2 Mean and root-mean-square (RMS) difference between true and mirrored midfacial complex

Study population		Mean distance (mm)	RMS (mm)
Total	Mean	0.14	0.87
	SD	0.12	0.21
	Min	0.002	0.56
	Max	0.881	1.98
Male	Mean	0.16	0.94
	SD	0.13	0.23
	Min	0.005	0.59
	Max	0.881	1.98
Female	Mean	0.11	0.81
	SD	0.1	0.17
	Min	0.002	0.56
	Max	0.547	1.48

respectively. Male patients showed a higher complete midfacial complex asymmetry (mean difference: 0.16 ± 0.13 mm, RMS: 0.94 ± 0.23 mm) compared to the female patients (mean difference: 0.11 ± 0.1 mm, RMS: 0.81 ± 0.17 mm). Moreover, a significant mean ($p = 0.034$) and RMS difference ($p = 0.002$) existed based on the gender of patients, where female patients were found to be significantly more symmetrical compared to the male patients.

Table 3 demonstrates the overall and gender-based mean and RMS difference between left/right true and mirrored sides. The comparison between superimposed true right and mirrored left models showed similar values (mean: 0.13 ± 0.11 mm, RMS: 0.82 ± 0.22 mm) compared to the true left and mirrored right models (mean: 0.13 ± 0.13 mm, RMS: 0.82 ± 0.21 mm), with no significant mean ($F = 0.158$, $p = 0.692$) and RMS difference ($F = 0.017$, $p = 0.896$) existed between both sides. A significant difference existed between males and females either for mean ($F = 6.6$, $p = 0.011$) or RMS value ($F = 22.06$, $p = < 0.001$). Interaction between side and gender was negligible for both measurements (mean: $F = 0.069$, $p = 0.794$; RMS: $F = 0.232$, $p = 0.631$).

Discussion

In a clinical practice, quantification of a normal midfacial complex symmetry in a healthy population could have a strong impact on the reconstructive surgical procedures where mirroring of the contralateral healthy part acts as a clinical reference for the restoration of unilateral defects. This quantification could provide a reference to the surgeons for achieving optimal treatment planning in terms of facial esthetics and function and follow-up evaluation.

At present, mirroring techniques for craniomaxillofacial reconstructive surgery are based on the assumption that both left and right sides are symmetrical. However, evidence suggests that a normal acceptable range of skeletal asymmetry exists, referred to as fluctuating asymmetry [32, 33]. This range has been mostly defined for skeletal structures such as the mandible, zygomatic bone, zygomaticomaxillary complex and orbital region. To our knowledge, no study exists assessing the symmetry of the midfacial complex in a healthy population group. Hence, the following study was conducted to three-dimensionally quantify the average natural variation in its symmetry.

Recently, various 3D workflows have been established for the restoration of unilateral skeletal defects and assessing symmetry [15–17, 34]. Although the mirroring and registration steps have been automated, the main limitation associated with these workflows has been the application of semi-automated skeletal segmentation tools which might negatively impact the final expected outcome. Furthermore, the cortical bone of the midfacial complex is thin and fibrous in nature with a low bone mineral density, which makes segmentation challenging and prone to error and variability [35, 36]. Therefore, the current study applied a state-of-the-art CNN-based automated segmentation tool. At present, no completely automated workflow exists in the literature for mirroring reconstructive surgical procedures. The proposed tool not only allowed automatization of the 3D workflow for re-establishing contralateral midfacial complex, but it could also act as a viable alternative for assessing symmetry by

Table 3 Mean and root-mean-square (RMS) difference between true left/right and mirrored sides

Study population		Mean right-left mirror (mm)	Mean left-right mirror (mm)	RMS right-left mirror (mm)	RMS left- right mirror (mm)
Total	Mean	0.13	0.13	0.82	0.82
	SD	0.11	0.13	0.22	0.21
	Min	0.003	0.004	0.546	0.49
	Max	0.872	0.902	2.08	1.87
Male	Mean	0.15	0.16	0.89	0.88
	SD	0.13	0.14	0.25	0.22
	Min	0.034	0.014	0.609	0.561
	Max	0.872	0.902	2.08	1.87
Female	Mean	0.11	0.11	0.74	0.76
	SD	0.07	0.12	0.15	0.19
	Min	0.003	0.004	0.546	0.49
	Max	0.349	0.62	1.27	1.43

providing a consistent and time-efficient segmentation. Furthermore, the symmetry was assessed based on the geometric morphometry of the whole bone surface instead of relying on specific landmarks and linear/angular measurements which could also offer a more realistic approach toward quantifying the site and magnitude of symmetry [10].

A comparison with prior evidence was deemed difficult owing to the absence of studies evaluating the symmetry of midfacial complex. Rather, the majority of studies focused toward the symmetry assessment of individual skeletal structures, such as orbital bone [14, 15], zygomatic arch [16, 17], mandible [37, 38] and upper skull [39, 40]. It is noteworthy that the assessment of midfacial complex symmetry as a whole is equally important as individual anatomical structures for defining facial form and function especially in major reconstructive surgical procedures where the whole unilateral complex region might require mirroring for reconstruction.

The findings of the present study showed that the overall asymmetry RMS value of the complete midfacial complex was comparable to that of zygomatic bone [16, 17] and orbital floor [14, 15]. On the contrary, the mean difference was found to be smaller compared to that of the upper skull. Based on gender variability, the present study showed a significant difference based on the mean and RMS values. These gender-based findings were contradictory to Gibelli et al. [16] study, where the authors reported no significant asymmetry of zygomatic bone for both types of values. In contrast, our findings were consistent with Ho et al. [17] study which reported significantly higher asymmetry in male patients. Previous studies also suggest that female skulls are more symmetrical compared to male skulls, which could also apply to the midfacial complex region. Furthermore, Hingsammer et al. [41] reported a mean zygoma asymmetry of 1.6 mm which was higher than the values obtained for the complex in the present study. This could be attributed to either the structural variability or the difference in methodology, where the authors relied on landmark-based linear measurements which fail to provide the true 3D symmetry of an anatomical structure and are more prone to human error and variability. In contrast, assessment of the entire skeletal structure using mirroring and part comparison provides more accurate and realistic information about symmetry.

Our findings also suggested no significant difference between left and right sides which was consistent with the studies evaluating upper skull and orbital floor. The presence of slight fluctuating asymmetry justifies mirroring reconstructive techniques in cases with unilateral defects and also confirms that no precipitating random difference exists on either side which might impact the final treatment plan [42].

The low magnitude of error and excellent observer reliability support the clinical applicability of the proposed methodology. The presented data suggested that the average amount of both complete and split midfacial complex asymmetry was within a clinically acceptable range of 1 mm, which signifies the rationale of using contralateral unaffected side as an acceptable reference for performing unilateral reconstructive surgery of the midfacial complex in traumatic and oncologic patients. Although minimal differences existed based on the gender of the patient, female patients showed a significantly more symmetrical complete midfacial complex compared to male patients, hence, implying that a surgeon should carefully examine any pre-existing asymmetry of the midfacial skeletal structures especially in male patients during the preoperative treatment planning phase. It should also be noted that the minimum and maximum values of asymmetry varied for each patient at an individual level.

Thereby, a patient-specific or personalized approach should be applied for planning midfacial reconstructive surgery instead of relying on a traditional one-size-fits-all approach [43].

The main strengths of the study included first-time reporting of the objective assessment of midfacial complex symmetry in a healthy population and the introduction of a reliable, accurate and efficient segmentation tool which could further automatize the symmetry assessment task and overcome the negative impact of thresholding-based approaches. At the same instance, the study had certain limitations. Firstly, the amount of asymmetry associated with each individual anatomical structure was not evaluated where one structure might influence the asymmetry more than the other, hence requiring further studies to establish automated segmentation approaches of individual structures to increase the clinical feasibility of the approach. Secondly, the symmetry evaluation of the left versus right side was based on an operator-dependent landmark-based midsagittal plane. Although this plane has been documented to be clinically acceptable for assessing symmetry, there is still a need for further research to also automate this task to ensure an operator-free approach.

Conclusion

The comparison between true and mirrored complete and split midfacial complex showed differences within a clinically acceptable range of 1 mm, which justifies the applicability of mirroring technique. These presented data could act as a reference for surgeons when evaluating asymmetry and guide the decision-making process for restoring midfacial defects. Furthermore, the proposed automated approach could act as a viable alternative for a more precise diagnosis, surgical planning, and follow-up evaluation.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research. Ethical approval was obtained from the Ethical Review Board of the University Hospitals Leuven (reference number: S57587).

Informed consent For this type of study, formal consent was not required.

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