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A three-dimensional CBCT-based vertical cephalometric analysis in adult patients

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Research Article

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Abstract

Background

This study aimed to apply a 3D vertical cephalometric analysis to evaluate vertical skeletal relationships in adult patients.

Methods

The CBCT data of ninety-seven first-visit adult patients were retrospectively selected and imported into MIMICS software. 3D visual models were constructed, and FH-PP, FH-OP, FH-MP, Jaraback ratio (SGo/NMe), CoGo, and GoMe were measured in three dimensions.

Results

The FH-MP and FH-OP, Jaraback ratio and CoGo, GoMe and CoGo were all significantly and positively related. The significant and negative correlations were found between CoGo and FH-OP, CoGo and FH-MP, Jaraback ratio and FH-OP, Jaraback ratio and FH-MP. No significant correlation was found between FH-PP and any other variables.

Conclusions

The 3D vertical cephalometric analysis revealed meaningful correlations among vertical skeletal parameters in adult patients, giving reference to orthodontic diagnosis and treatment outcome evaluation.

Background

Three-dimensional (3D) evaluation of patients' facial skeletal pattern has been recognized as an indispensable part of diagnosis and treatment planning in orthodontics and orthognathic surgery [1]. As the most commonly used imaging modality in clinical practice, cone-beam computed tomography (CBCT) enables detailed assessment of craniofacial skeletal structures [2]. While all three spatial dimensions are important, the vertical dimension has consistently been a primary focus due to its influence on facial aesthetics, growth patterns [3], and treatment outcomes [4, 5].

Two-dimensional (2D) cephalometrics, initially introduced by Broadbent and Hofrath in 1931, has been a fundamental and routinely used assessment tool throughout the orthodontic treatment process [6]. Although numerous 2D cephalometric vertical parameters exist, not all of them can provide equivalent diagnostic consistency or clinical interpretability [7]. Among the commonly used quantitative measurements, the most widely used variables include FH-MP, FH-OP, and FH-PP. Additionally,

Jaraback's ratio (SGo/NMe), ramus height (CoGo), and mandibular body length (GoMe) have been important descriptors of vertical facial morphology [8].

With the advent and widespread clinical use of CBCT over the past two decades [9], an increasing number of studies have focused on 3D cephalometric analysis [10]. Studies have confirmed that linear and angular measurements derived from 3D CBCT models are more accurate and reliable than 2D cephalometric analysis [11, 12]. Additionally, quantitative comparisons between CBCT and reconstructed lateral cephalograms have shown that CBCT provides a more reliable representation of anatomical structures and reduces bias associated with planar projection, especially for measurements outside the mid-sagittal plane [13].

Despite the advantages of 3D imaging, the lack of standardized and widely accepted protocols for 3D vertical assessment has limited its routine use in clinical research [14, 15]. Consequently, many contemporary studies continue to rely on traditional 2D cephalometric measurements for vertical evaluation, even when CBCT data are available [16, 17, 18]. This situation highlights the need for validated and standardized 3D vertical cephalometric assessment methods [19].

This study aimed to apply 3D CBCT-based cephalometric analysis to evaluate vertical skeletal relationships and mandibular morphology in orthodontic patients.

Methods

This study was approved by the Research Ethics Committee of Qingdao Municipal Hospital and complies with the Declaration of Helsinki. Among the outpatients who visited the Department of Stomatology, Qingdao Municipal Hospital in 2024, CBCT scans were selected from the database of orthodontic patients at initial presentation. The inclusion criteria were as follows: (1) Adult patients with permanent dentition (age > 18), (2) all teeth erupted to the occlusal plane with no teeth missing. The exclusion criteria were as follows: (1) any of the first molars and the first bicuspids have caries, restoration, or extensive wear; (2) acquired or inherited dentofacial deformities, including cleft, craniofacial syndrome, or posttraumatic deformity, (3) craniofacial asymmetry, including obvious mandibular deviation (the distance from Me to the midsagittal plane larger than 2 mm) [20], (4) previous orthodontic, orthopedic, or orthognathic treatment.

CBCT scans (i-CAT model 17–19; Imaging Sciences International, Hatfield, Pa) were retrospectively selected from a database of patients' initial visit records. The scanning settings were as follows: 120 kV, 5 mA, exposure time of 10 s, voxel size of 0.25 mm, axial slice thickness of 0.3 mm, and scanning area of head and neck. The digital imaging and communications in medicine (DICOM) data were exported and transferred into Materialise's interactive medical image control system (MIMICS, version21.0 0; Materialise, Leuven, Belgium) software. 3D virtual models of the skulls were reconstructed, and the head positions were reoriented. Subsequently, following the instruction of Swennen et al. [21], the points were located firstly and directly on the 3D models, then calibrated in axial, coronal, and sagittal views,

respectively. The measuring points and planes were shown in Figures I and II, and the definitions were shown in Tables I and II.

Table I. The definitions of three-dimensional landmarks.

Points	Definitions
Sella turcica (S)	The central point of the hypophyseal fossa
Left Gonion (GoL)	The point at left mandibular angle that is defined by dropping a perpendicular from the intersection point of the tangent lines to the posterior margin of the left mandibular vertical ramus and inferior margin of the left mandibular body
Right Gonion (GoR)	The point at right mandibular angle that is defined by dropping a perpendicular from the intersection point of the tangent lines to the posterior margin of the right mandibular vertical ramus and the inferior margin of the right mandibular body
Menton (Me)	The most inferior midpoint of the chin on the outline of the mandibular symphysis
Nasion (N)	The midpoint of the frontonasal suture
Anterior nasal spine (ANS)	The most anterior midpoint of the anterior nasal spine of the maxilla
Left posterior nasal spine point (LPNS)	The point of maximum concavity of the posterior border of the palatal bone in the horizontal plane at the left side
Right posterior nasal spine point (RPNS)	The point of maximum concavity of the posterior border of the palatal bone in the horizontal plane at the right side
Right first molar point (R6)	The occlusal point of the mandibular right first molar
Left first molar point (L6)	The occlusal point of the mandibular left first molar
Right first premolar point (R4)	The occlusal point of the mandibular right first premolar
Left Orbitale (LOr)	The most inferior point of the left infra-orbital rim
Right Orbitale (ROr)	The most inferior point of the right infra-orbital rim
Porion (Po)	The most superior point of left external acoustic meatus
Left condylion (CoL)	The most postero-superior point of the left mandibular condyle
Right condylion (CoR)	The most postero-superior point of the right mandibular condyle

Table II. The definitions of three-dimensional measuring planes.

Planes	Definitions
Frankfort horizontal plane (FH)	Connecting the LOr, ROr, and Po.
Palatal plane (PP)	Connecting ANS, LPNS, and RPNS
Functional occlusal plane (OP)	Connecting R6, R4, and L6
Mandibular plane (MP)	Connecting GoL, GoR and Me.
Mid sagittal plane (MSP)	A plane constructed through the S-N line and perpendicular to the Frankfort horizontal (FH) plane.

The definitions of 3D linear and angular measurements were shown in Table III. An innovative 3D Jaraback ratio analysis protocol was introduced. Firstly, considering the difference in transverse dimensions, the NMe should not be the direct 3D distance from point N to point Me, but the projected length of it on the midsagittal plane. Secondly, the SGo was calculated through three directly measured 3D distances: SGoL, SGoR, and GoLGoR; the distance between the point S and the midpoint of bilateral Go could be calculated to be the final variable SGo (The calculation protocol was shown in Table III and Figure III). Thirdly, the Jaraback ratio could be accurately calculated through SGo/NMe, despite the bias in the transverse dimension in this way.

Table III. The definitions of three-dimensional linear and angular measurements

Measurements	Definitions
FH-PP	Three-dimensional angulation between the FH plane and the PP plane
FH-OP	Three-dimensional angulation between the FH plane and the OP plane
FH-MP	Three-dimensional angulation between the FH plane and the MP plane
CoGo	Measure the 3D distance from CoL to GoL, then measure the distance from CoR to GoR, the means of the bilateral values were calculated as CoGo
GoMe	Measure the 3D distance from GoL to Me, then measure the distance from GoR to Me, the means of the bilateral values were calculated as GoMe
SGo	The three-dimensional distances from S to GoL, from S to GoR, and between GoL and GoR were measured. The distance SGo, defined as the distance from S to the midpoint of the bilateral gonion points, was subsequently calculated based on geometric relationships within a triangle.
NMe	Measure the direct 3D distance from N to Me, then measure the distance from Me to MSP, then the vertical component of the 3D N-Me distance was calculated using the Pythagorean theorem
Jaraback ratio	Jaraback growth pattern evaluation, defined as the ratio of posterior facial height to anterior facial height (SGo/NMe)

As for the bilateral measurements CoGo and GoMe, the mean value of both sides was used for subsequent analysis. Landmark identification and 3D measurements were performed by the same examiner (Fangshuo Wang) two times, with a time interval of two weeks; the means were calculated to represent the final measurement.

Power analysis was performed using Power Analysis and Sample Size (PASS, version 15.0; NCSS, LLC, Kaysville, Utah) software based on a Spearman rank correlation. A moderate effect size ($\rho = 0.35$) was

assumed according to commonly accepted guidelines for correlation coefficients [22], with a two-sided significance level of 0.05 and a desired power of 0.90. Therefore, 97 samples were needed. The intraclass correlation coefficients (ICC; 2-way random, single measurements) were used to assess the intraexaminer reliability. The agreement was classified according to the following ICC values [23]: excellent (0.9), good (0.75–0.9), moderate (0.5–0.75), or poor (< 0.5). The Shapiro-Wilk tests were performed to test the normal distribution. The linear and angular measurements were all normally distributed except the CoGo measurements ($P < 0.05$). Therefore, Spearman correlation coefficient analyses were performed to assess the correlation among the six variables.

Results

Ninety-seven patients (28 males and 69 females, mean age 24.61 ± 6.16 years) were included in this study. There were 36 Skeletal Class I patients, 30 Class II patients, and 31 Class III patients, according to the initial 2D cephalometric analysis. Except for the ICC value of 0.613 for the parameter CoGo, the ICC values were all above 0.85, indicating good to excellent reliability. The means, standard deviations, and the reliability of the measurements were shown in Table IV. As for the results of Spearman correlation coefficient analyses, correlations with $P < 0.01$ were considered statistically significant. The FH-MP & FH-OP, Jaraback ratio & CoGo, GoMe & CoGo were all significantly and positively related. The significant and negative correlations were found between CoGo and FH-OP, CoGo and FH-MP, Jaraback ratio and FH-OP, Jaraback ratio and FH-MP. No significant correlation was found between FH-PP and any other variables. The correlation coefficients were presented in Table V.

Table IV. Descriptive statistics and intra-examiner reliability of three-dimensional cephalometric measurements

Variables	Descriptive statistics	ICC (95%CI)
FH-OP (°)	3.05 ± 4.72	0.864 (0.803–0.907)
FH-PP (°)	-6.14 ± 3.49	0.854 (0.752–0.910)
FH-MP (°)	19.97 ± 5.39	0.934 (0.901–0.956)
CoGo(mm)	60.52 (57.42–64.36)*	0.613 (0.472–0.724)
GoMe(mm)	83.08 ± 4.52	0.931(0.899–0.953)
Jaraback ratio	0.68 ± 0.05	0.929(0.895–0.952)

*:CoGo (mm) showed a non-normal distribution and was reported as median (IQR).

Table V. Correlation coefficients among six variables

variable	1	2	3	4	5	6
1.FH-OP	-					
2.FH-PP	0.103	-				
3.FH-MP	0.507*	0.177	-			
4.CoGo	-0.334*	0.071	-0.374*	-		
5.GoMe	-0.17	-0.024	-0.109	0.412*	-	
6.Jaraback	-0.369*	0.018	-0.722*	0.593*	0.021	-
*: Indicates a statistical significance at P < 0.01						

Discussion

The present 3D cephalometric analysis revealed meaningful correlations among vertical skeletal parameters and mandibular morphological characteristics in adult patients, which is in agreement with the results of previous 2D studies [24, 25]. In addition, the presence of coherent and directionally appropriate relationships in our study could contribute to a more integrated understanding of vertical craniofacial structure in orthodontic diagnosis.

Before interpreting the clinical implications of these findings, the reliability of the CoGo measurements warrants consideration. The reproducibility of the location on Co point was relatively low, which is in corporate with the study of Lisboa et al. [26]. It might be attributed to the intrinsic anatomical factors. The condylar head presents a rounded and continuous surface without distinct anatomical edges, which makes the identification of a single, reproducible landmark challenging in 3D space. In addition, individual anatomical differences among the samples, and sensitivity to head orientation may further increase variability [27]. Nevertheless, this limitation was carefully considered and did not affect the overall conclusions.

Given the potential influence of craniofacial asymmetry in the samples, two methodological considerations were specifically addressed in the present study. One aspect is that to minimize potential measurement bias, patients with dentofacial deformities and craniofacial asymmetry were excluded from the present study. The reason is that in the presence of asymmetry, the MP, OP, and PP may exhibit canting [28] in the coronal dimension. Under such conditions, the angles measured between these planes and the FH plane do not exclusively reflect their true sagittal inclination, but represent composite angles resulting from the anteroposterior tilt and the coronal canting. Another aspect is that in previous studies, such as that by Sahlsten et al. [29], anterior facial height was quantified as a point-to-point 3D distance between N and Me. This approach reflects the overall spatial relationship between two landmarks, but it might be influenced by transverse deviations in patients with facial asymmetry. In our study, apart from the special exclusion criteria, the NMe was measured as its projection onto the mid-sagittal plane, which minimized the effect of lateral displacement.

Clear Correlations were found among the measured parameters. The FH-OP was significantly correlated with the FH-MP, Jarabak ratio, and ramus height (CoGo), indicating that patients with a steeper occlusal plane are more likely to exhibit a hyperdivergent growth pattern and an increased mandibular ramus height. In contrast, the FH-PP angle showed no significant correlation with any of the analyzed variables, suggesting that the FH-PP angle may be less appropriate for evaluating the overall cranial vertical relationship, but rather more reflective of maxillary morphology. The strongest correlation coefficient (r= -0.722) was observed between the FH-MP and the Jarabak ratio, indicating that both parameters derived from 3D measurements can effectively serve as indicators of vertical skeletal relationships. Additionally, GoMe was positively correlated only with CoGo, suggesting that the observed inter-individual differences primarily reflected variations in mandibular size. Although these findings do not imply causal relationships among the parameters, they support the applicability for integrated assessment of vertical skeletal relationships, giving reference to orthodontic diagnosis and treatment outcome evaluation.

There are some limitations of our study. First of all, the samples were retrospectively selected from the database of patients with malocclusion; consequently, the findings of this study do not allow for the establishment of normative ranges. Second, ethnically diverse populations should be incorporated to enhance generalizability. Third, to establish a robust, standardized, and widely applicable approach, multiple raters should be involved to assess the inter-examiner reliability; validity and diagnostic agreement [30] should also be evaluated. In the future, artificial intelligence-based automatic landmarking and vertical relationship assessment are expected to become an important focus of future research and clinical application.

Conclusions

The 3D vertical cephalometric analysis revealed meaningful correlations among vertical skeletal parameters in adult patients, giving reference to orthodontic diagnosis and treatment outcome evaluation.

Abbreviations

CBCT: Cone-beam computed tomography; 3D: three-dimensional; 2D: Two-dimensional; DICOM: digital imaging and communications in medicine; PASS: Power Analysis and Sample Size; ICC: intraclass correlation coefficients. The abbreviations of the measured variables were shown in Table I and II.

Declarations

Ethics approval and consent to participate

This study was approved by the Research Ethics Committee of Qingdao Municipal Hospital and complies with the Declaration of Helsinki. The written informed consents were received from the patients. In addition, as this study was approved and registered as a project by the Shandong Provincial Health Commission at the end of the year 2023 (the project title and reference number are provided in

the Funding section below), ethical review had already been conducted by the Ethics Committee of Qingdao Municipal Hospital prior to project application. To avoid duplicate numbering, the ethics committee did not issue a separate approval reference number for this study.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Fangshuo Wang contributed to methodology, investigation, repeat measurements, and original draft preparation; Liying Chen contributed to investigation and statistical analysis; Xiao Xu contributed to data acquisition and supervision. Rongtao Yuan contributed to the original draft, figures, and tables preparation; Chunxi Zhang contributed to conceptualization, methodology, project administration, manuscript review, and editing.

Acknowledgments

Not applicable

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Figures

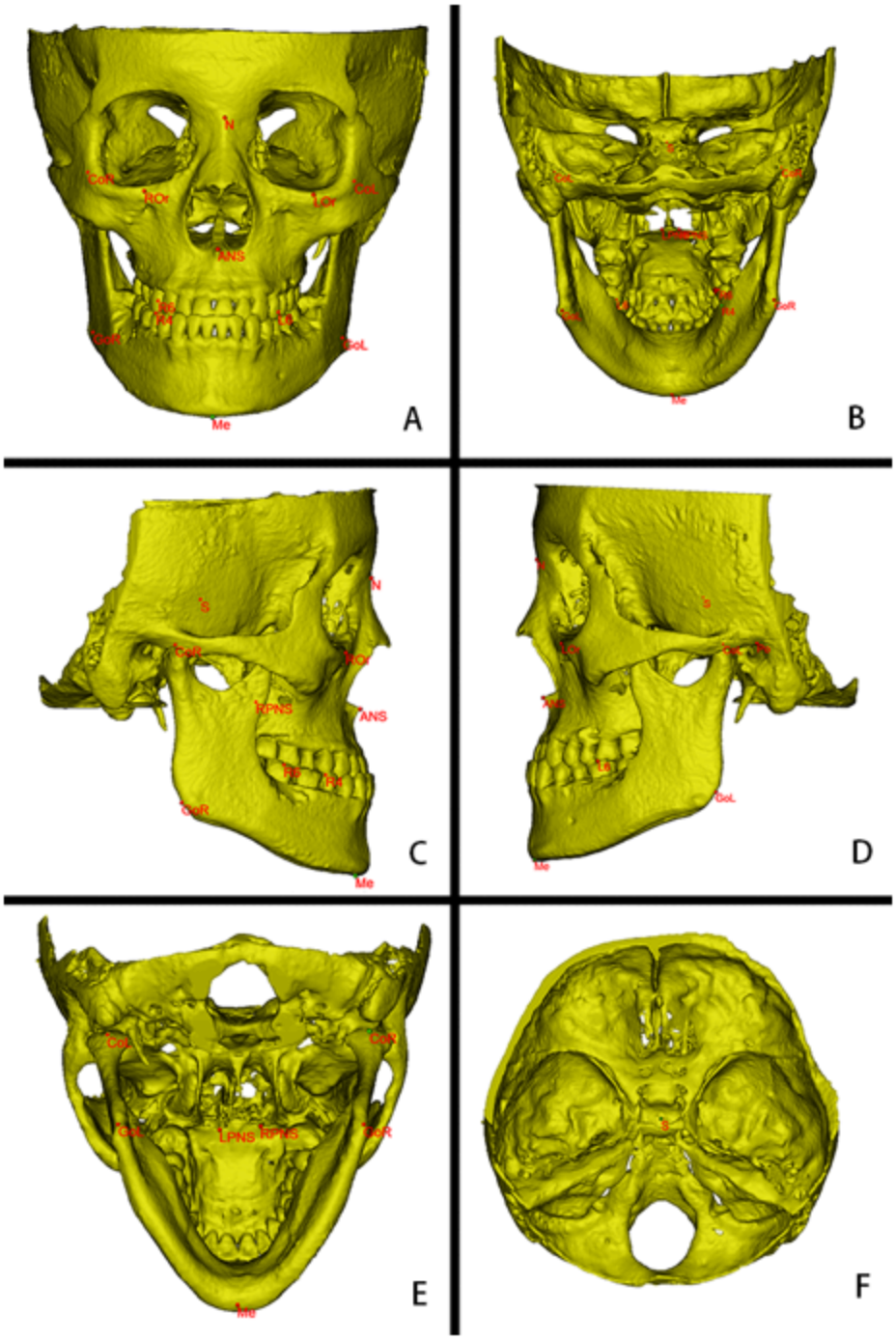


Figure 1

The measuring points on 3D reconstructed models.

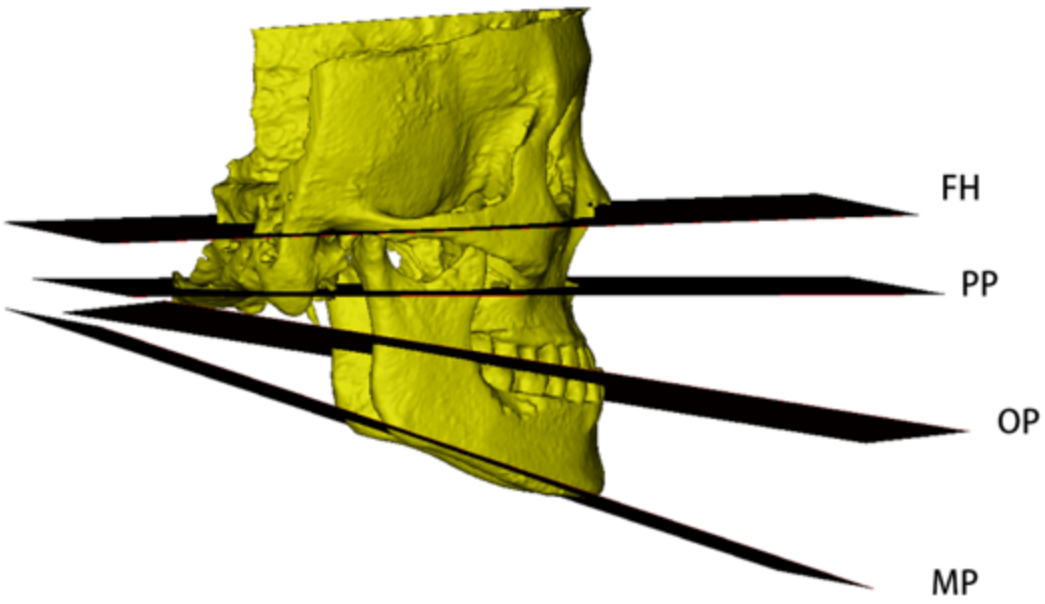


Figure 2

The 3D measuring planes.

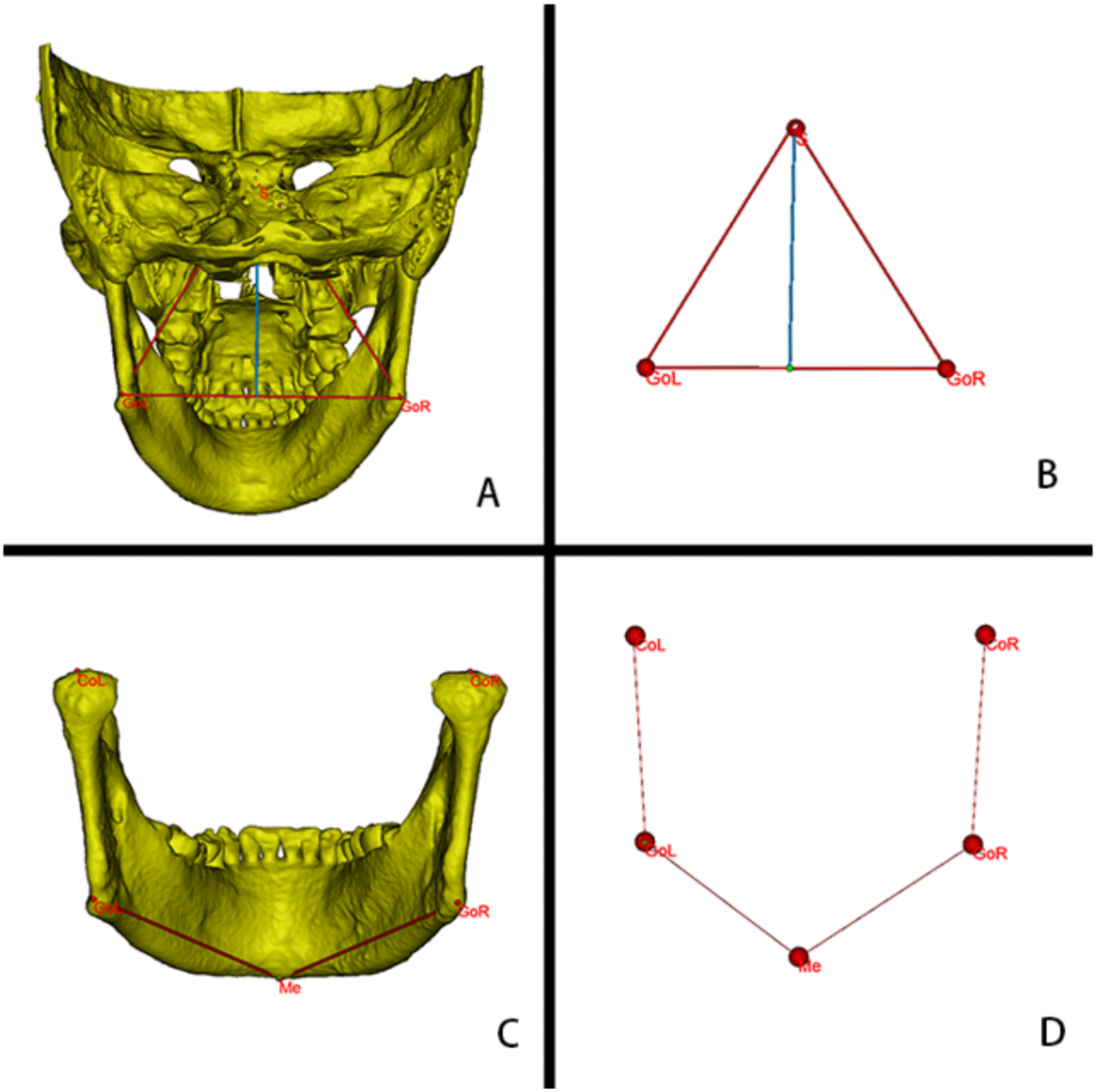


Figure 3

A and B, the 3D measurements and calculation of SGo. C and D, the linear measurements of bilateral CoGo and GoMe.