

3D Positioning of the Mandibular Head Using Radiographic Anatomical Landmarks

Oleg V. Slesarev¹, Karina T. Sargsyan^{1*}, Marina V. Komarova², and Larisa T. Volova¹

¹Samara State Medical University, 89 Chapaevskaya str., Samara 443099, Russian Federation

²Samara National Research University, 34 Moskovskoe Shosse, Samara 443086, Russian Federation

*e-mail: sukasyan_karina@mail.ru

Abstract. Optimizing the analysis of radiographs of temporomandibular joint (TMJ) bone structures taken with cone beam computed tomography (CBCT) is an important topic in modern dentistry. The aim of the study is to establish stable correlations between the cranial indices obtained by cone-beam computed tomography (CBCT) of the cranial bones and the position of the mandibular condyle in the mandibular fossa. Student's t-test and Pearson's correlation coefficient were used in the study. Scattergrams and Altman plots were used to visualize the data. A critical p-value of 0.05 was assumed. Craniometric points and indices were determined to analyze the radiographic anatomical images of the cranial bones acquired by CBCT in axial projection. This data can be used for 3D modeling of the construction of a bioengineered mandibular head. By analyzing the CBCT scans of the cranial bones, we found that the intersection of the mid-sagittal and frontal planes forms an angle of 90 degrees. Stable craniometric coordinates of the median-sagittal and frontal planes were determined, allowing positioning of an endoprosthesis in the mandibular fossa of the temporal bone and subsequent correct fixation of the prosthesis to the mandibular branch. © 2024 Journal of Biomedical Photonics & Engineering.

Keywords: imaging of the temporomandibular joint; cone-beam computed tomography of the temporomandibular joint; radiographic anatomy of the temporomandibular joint; craniometry.

Paper #9117 received 19 Jun 2024; revised manuscript received 29 Aug 2024; accepted for publication 31 Aug 2024; published online 29 Sep 2024. [doi: 10.18287/JBPE24.10.030304](https://doi.org/10.18287/JBPE24.10.030304).

1 Introduction

Optimizing the analysis of radiographic images of temporomandibular joint (TMJ) bone structures obtained with cone-beam computed tomography (CBCT) is an important issue in modern dentistry [1–4]. CBCT is a high-tech and reliable research method suitable for performing long-term craniometric studies of the cranial bones based on X-ray images. This is supported by the prevalence of TMJ pathologies which are caused by various factors and can be combined with acquired or congenital deformities of the facial and cranial bones [5–7]. The modern requirements for the fabrication and implantation of mandibular head endoprostheses require the use of technologies not only for the precise fabrication of prototypes, but also for the exact anatomical positioning of the implant in the articular

fossa of the temporal bone to ensure proper function. The anatomical and functional approach allows for the personalization and customization of 3D implant designs using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs that enable the fabrication of custom TMJ implants using 3D printing technology [8].

Due to its complexity, the mandibular head or TMJ is the most challenging component for prototyping and bioengineering. For accurate 3D planning and manufacturing of the TMJ implant, it is essential to determine the exact craniometric landmarks of the joint, based on which the prototype is designed and manufactured. The correct calculation of the spatial position of the TMJ endoprosthesis in relation to other cranial bones is possible with the help of craniometric landmarks from X-ray images taken with cone beam

computed tomography (CBCT). Nowadays, it has become clear that 3D modeling should be based on these landmarks which reliably determine the position of the TMJ in the skull. This enables not only 3D modeling of the anatomy of the TMJ, but also the planning of its placement at the recipient site. The precise fabrication of a bioengineered prosthesis will make it possible to fully meet the anatomical and functional requirements of oral surgery using regenerative medicine techniques. The use of CBCT enables reliable and highly accurate assessment of linear (dimensional) and volumetric (3D) differences between paired anatomical structures of the craniomandibular complex [9]. Therefore, the identification of cranial landmarks for the analysis of radiographic images of TMJ bone structures obtained by cone beam computed tomography (CBCT) and 3D modeling of a customized TMJ implant is a promising area in maxillofacial surgery using regenerative medicine techniques.

The aim of the study is to develop craniometric indices based on CBCT scans of the skull bones to determine the position of the mandibular head in the mandibular fossa (socket) of the temporal bone.

2 Materials and Methods

2.1 Description of the Sample

To achieve the aim of this study, a retrospective analysis of 111 patient cases from the maxillofacial surgery departments of the clinics of Samara State Medical College ($n = 90$) and Medline Dental Clinic ($n = 21$), who underwent CBCT of the facial and cranial bones in Samara between 2018 and 2023, was performed. The age of the patients ranged from 20 to 64 years, with 35 women and 76 men included. The analysis revealed that CBCT scans of the skull were performed to make a definitive diagnosis, including 65 cases of fractures of the mandibular condyle, 19 cases of benign neoplasms of the mandible, 6 cases of postoperative deformities of the mandible, and 21 cases of TMJ disorders without

radiologic or anatomic evidence of pathology of the facial bone. The study protocol was reviewed and approved by the Ethics Committee of Samara State Medical College. The study sample consisted of 21 asymptomatic Caucasian individuals, 14 women and 7 men, aged between 25 and 64 years with an average age of 32.5 years.

The data used for the study included information from the medical history and clinical examinations as well as CBCT scans of the TMJs in habitual occlusion. Subjects were selected based on clinical records from 111 initial visits to the Department of Oral and Maxillofacial Surgery at the clinics of Samara State Medical College and Medline Private Dental Clinic.

To ensure that the results were not influenced by growth-related distortions in the positioning of the condyles, only people who had not suffered facial trauma or had undergone surgery within the last five years were included in the study [10]. Patients in stages 4, 5 or 6 of cervical vertebral maturation were also excluded from the study [11]. A surgeon with 5 years of experience was involved in all clinical evaluations and radiologic analyzes of the TMJ.

2.2 Study Design

The study included 21 patients who underwent CBCT and whose diagnosis was consistent with the study protocol: no pathologic changes in the facial and cranial bones and no abnormalities in the radiologic anatomy of the TMJ. Patients with fractures of the maxilla or mandible, tumors of the maxilla or mandible, or TMJ ankylosis were excluded (Fig. 1).

The patients in the study group ($n = 21$) gave their informed consent for the radiological examination. Computed tomography (CT) of the facial and cranial bones was performed in a specialized facility with a state license for this type of service. We used a CT scanner with a voxel resolution of 0.3 mm on the Planmeca ProMax 3D Classic machine (Finland).

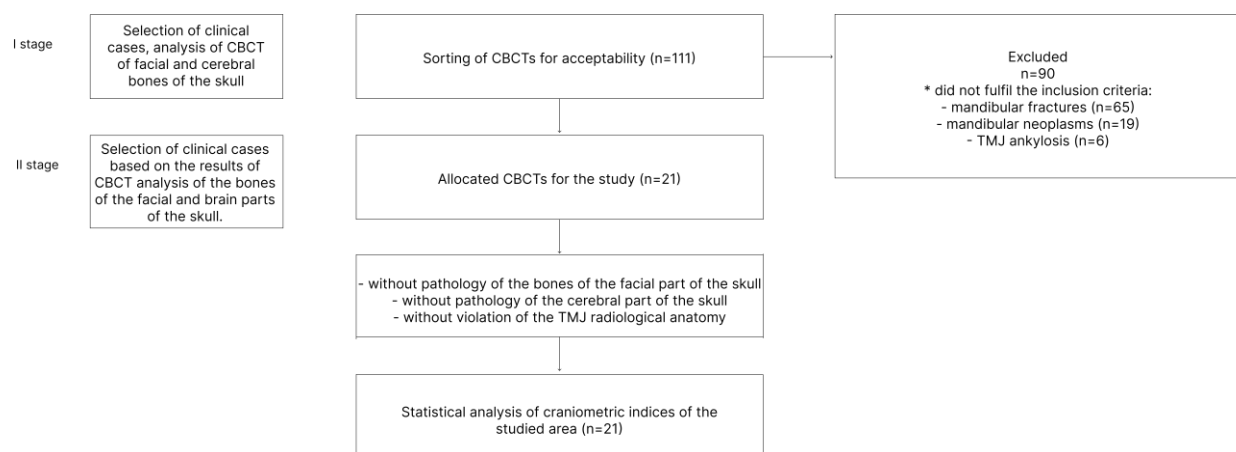


Fig. 1 Flowchart of patient selection for the study.

For all the subjects, we selected the “M” (adult) imaging mode, in which the voltage of the X-ray tube is automatically set to 90 kV and the current to 6.3 mA. The volume diameter was 50 mm, the height 80 mm and the dose-area product (DAP) 472 mg/cm² milligram-centimeters squared. The computed tomographic dose index (CTDY) was 4.6 mg.

2.3 Technique for Analyzing Radiographs of the Temporomandibular Joint by Craniometry

CBCT of the cranial bones was used to determine the radiographic anatomic landmarks for the position of the LFH within the mandibular fossa of the temporal bone.

1. Determination of the craniometric points

Radiographic anatomic landmarks of craniometric points that fulfill the criteria for a craniometric point were identified in the axial projection. The algorithm for determining craniometric points from the image of the cranial bones in the axial CBCT projection involves determining the mid-sagittal and frontal planes of the head and neck region (HNC) and the craniometric point of the HNC formed by the intersection of these planes; the determination of the craniometric points of the mandibular ramus, condyle and sphenoid bone; the construction of radiologic anatomic planes based on the craniometric points; and the determination of angular dependencies and stable radiologic anatomic relationships between the constructed planes. Thus, we can determine the topography of five craniometric points in the axial projection of the skull.

1.1 Craniometric measurement of the TMJ. To determine the topography of the contours of the TMJ in

the mandibular fossa of the temporal bone, one must first locate the peaks that protrude maximally into the maxillary sinus on the medial and lateral sides of the TMJ surface. Then one should mark these peaks with a marker and draw a straight line between them to determine the frontal axis of the TMJ. This axis should then be divided in half to obtain the craniometric center, which is the radiographic center of the frontal axis of the TMJ.

1.2 Craniometric point (suborbital opening (fi)): In the axial projection, the suborbital opening is defined by the opening of the infraorbital canal on the anterior wall of the maxillary sinus.

1.3 Craniometric point (coronoid process (pc)) – tip of the mandibular ramus: This point is determined in the axial projection of a cranial cone beam computed tomography (CBCT) scan (Fig. 2).

1.4 Craniometric point (The Cuneiform Part of the Vomit (pcv)): This is the wedge-shaped part of the condyle that protrudes the most from the lateral surface, as seen in the axial view of the cranial CBCT image (Fig. 2).

1.5 Craniometric point (sphenoid body (cs)): This is the body of the sphenoid bone that protrudes furthest from the lateral surface in the axial projection of the cranial computed tomography (CBCT) image (Fig. 2).

2. Construction of anatomical X-ray planes from cone beam computed tomography (CBCT) images of the skull in the axial projection.

2.1 Plane head mandibular mid sagittal (pcmms) – marked by the points: cm-fi.

The mid sagittal plane of the mandibular ramus (prms) is defined by the points sm-pc. The coronoid process (pc) and the mandibular branch lie in the same mid-sagittal plane as the PRMS, unlike other mid-sagittal planes.

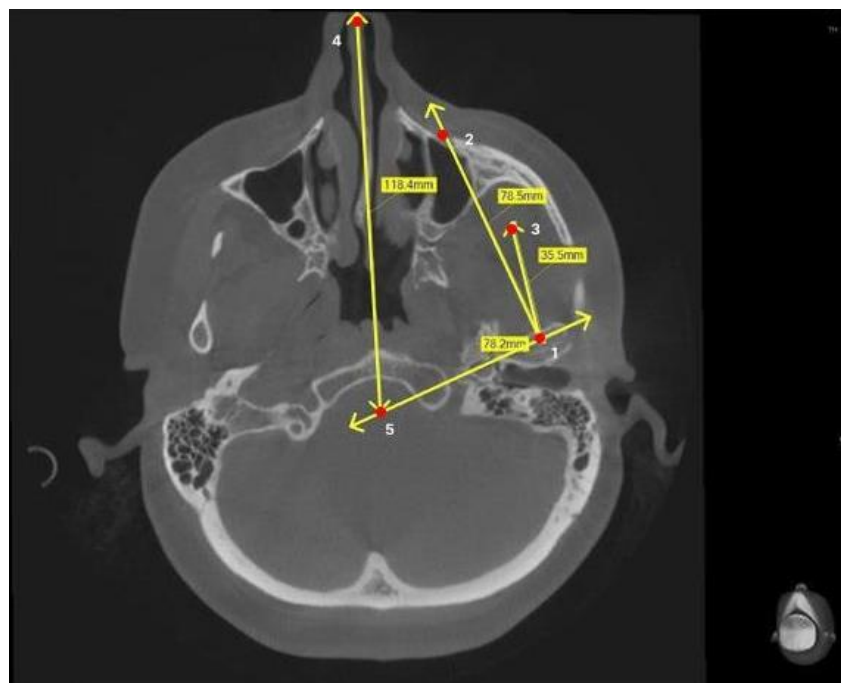


Fig. 2 Topography of the cranial points in the axial projection of the skull (1 – mandibular head (cm), 2 – infraorbital hole (fi), 3 – coronoid process (pc), 4 – the cuneiform part of the vomit (pcv), 5 – sphenoid body (cs)).

2.2 The skull plane mid sagittal (PCMS) is constructed by connecting the lateral edge of the scapula to the body of the sphenoid bone. To do this, one should mark the lateral and medial margins of the scapula and connect these points with a straight line to obtain the mid sagittal plane of the skull.

3. Determination of the radiographic anatomical relationships and dependencies between the angles formed at the intersection of the mid-sagittal plane and the frontal plane.

3.1 The angle msp-cm is formed by the mid-sagittal plane of the skull and the frontal plane of the LFG. This angle shows the relationship between the position of the mandibular head and the bones of the cerebral part of the skull (Fig. 3).

3.2 The angle fi-cm-pc: This angle is formed by the intersection of the medial sagittal plane of the LFG (left frontal gyrus) and the mandibular branch (Fig. 3).

3.3 The angle formed by the medial sagittal plane of the skull and the left frontal horn.

2.4 Statistical Analysis of the Data

The statistical analysis of the results was carried out using the SPSS 25 software package. The descriptive statistics were presented in the form of mean values and standard deviations ($M \pm SD$) as well as medians and quartiles (Me, Q1, Q3). The *t*-test for paired samples and Pearson's correlation coefficient were used for the analysis. Scatter plots and Altman diagrams were used to visualize the data. The significance level was set at 0.05.

3 Results

In this study, craniometric landmarks were identified and stable radiologic-anatomic relationships between them were established to develop a method for determining the

position of the laryngeal fossa (LFG) in the mandibular fossa of the temporal bone using CBCT imaging. Analysis of cranial bone CBCT scans in axial projection revealed that an angle of 90 degrees is formed in the head and neck complex (HNC) at the intersection of the mid-sagittal and frontal planes. Projection of the mid-sagittal LFG plane onto other parts of the skull showed that in most cases it passes through the subocular aperture, a landmark of the mid-sagittal plane on the outer surface of the face (Fig. 4).

The suborbital foramen is a stable anatomical structure which can be recognized on CBCT images in the axial projection and is located on the anterior wall of the maxillary sinus [12, 13]. In contrast to the mobile LNG, whose position is determined by the functional possibilities of the TMJ or pathological changes, the suborbital foramen provides a stable reference point for the construction of the mid-sagittal plane.

To construct the mid-sagittal plane, we need a second stable landmark that can be identified in the same location on axial CBCT images. In the presence of LFG, this landmark is the intersection of the mid-sagittal plane and the frontal plane of LFG. This information is crucial in clinical situations where it is difficult or impossible to determine the center of the LFG based on average anatomical parameters, such as fractures of the mandibular condyles with displacement or absence of the LFG for other reasons. To determine this, we identify a stable and immobile TMJ formation – the mandibular fossa of the temporal bone – on the CBCT image in axial projection.

A circle is then inscribed around the projection of the contours of this structure, and the center of this circle is taken as the center of the TMJ. Using this method, we can determine the mid-sagittal plane of the TMJ both with and without the joint.

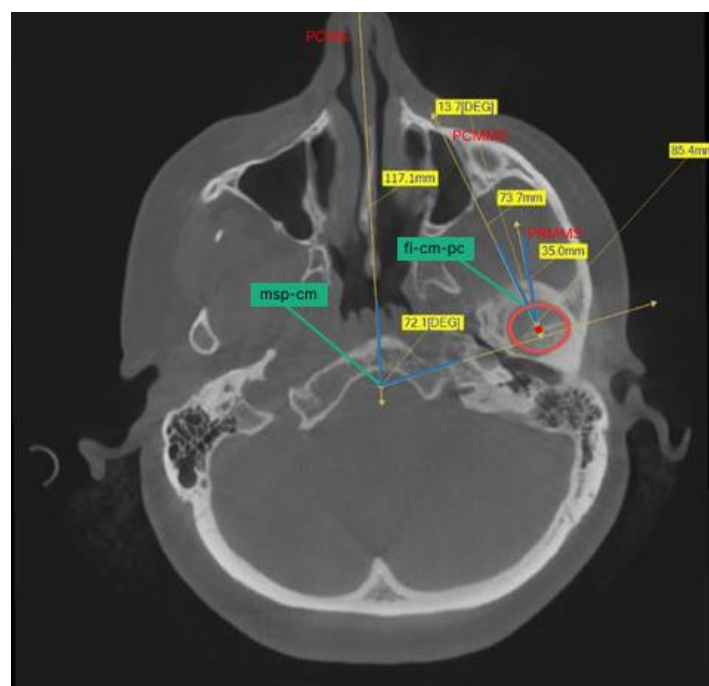
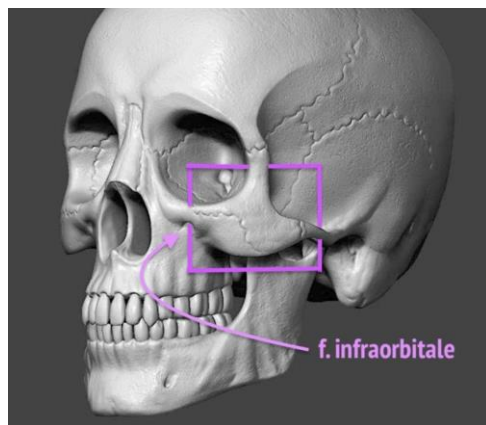
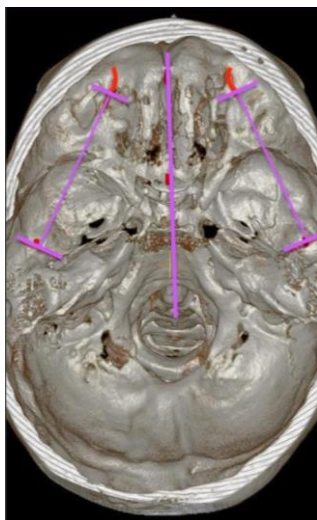


Fig. 3 Angles formed at the intersection of the mid-sagittal plane and the frontal plane.



(a)



(b)

Fig. 4 The suborbital foramen is a landmark in the median-sagittal plane on the outer surface of the face.

By drawing a straight line through the maximum mesio-distal dimension of the mandibular head and

dividing it into two equal parts, we found the center of the frontal plane of the LFG. We drew a line from the suborbital foramen to the center of the frontal plane of the LFG. Then we drew a plane from point CM to point PC and obtained the angle $fi-cm-pc$ at the intersection of these two planes. The value of this angle allowed us to determine the angle of deviation of the midsagittal plane of the LFG from the mid-sagittal plane of the mandibular branch. Thus, the angle formed by the median-sagittal planes of the LFG and the mandibular branch ranged from 2.5 to 4.4 degrees. This information should be taken into account when modeling NIRs used in reconstructive surgery, TMJ arthroplasty or total mandibular fragment replacement.

In order to assess the stability of the relationship between the obtained craniometric indices, we decided to virtually simulate the absence of the mandibular head and perform measurements using the same methodology. Instead of the mandibular head, we used the contours of the mandibular fossa as bony landmarks on a CBCT of the cranial bones in an axial projection.

The construction of the inscribed circles and the determination of the centers of these circles (craniometric points) on the CT scans of the patients were performed using our previously developed method [14]. The presence of systematic differences in the estimates of the angles with and without consideration of the position of the mandibular head was determined using the paired Student's t -test (Table 1). No such discrepancies were found for the $fi-cm-pc$ angle. The errors in the direction of increase and decrease of this angle occurred approximately equally often and averaged 0.75 degrees ($p = 0.067$), the 95% confidence interval (CI) of the difference includes zero and is -0.06 to $+1.56$ degrees. However, a different picture emerged for the $msp-cm$ angle. There was a systematic error in its measurement. It was found that the estimate of this angle in the absence of the mandibular head was underestimated by an average of 3.10 (95% CI: 1.22–4.98) degrees compared to the measurements with the mandibular head present.

Table 1 Comparison of angles performed in the presence and absence of the mandibular head.

Angle	In the presence of the lower jaw head (1) M $\pm$ SD	In the absence of head the lower jaw (2) M $\pm$ SD	Difference between angles 1 and 2 M (95% CI)	p
Angle $fi-cm-pc$, deg	19.32 $\pm$ 3.04	18.41 $\pm$ 2.89	0.75 (−0.06 ... +1.56)	0.067
Angle $msp-cm$, deg	70.76 $\pm$ 3.80	67.23 $\pm$ 3.50	3.10 (+1.22 ... +4.98)	0.003

Table 2 Characterization of the differences in the angle measurements with and without the mandibular head present: absolute value of the differences.

Angle	Median	Lower quartile Q1	Upper quartile Q3	Minimum	Maximum
Absolute differences $fi-cm-pc$, deg	1.60	0.40	2.50	0.00	4.40
Absolute differences $msp-cm$, deg	2.50	0.85	7.05	0.00	11.30

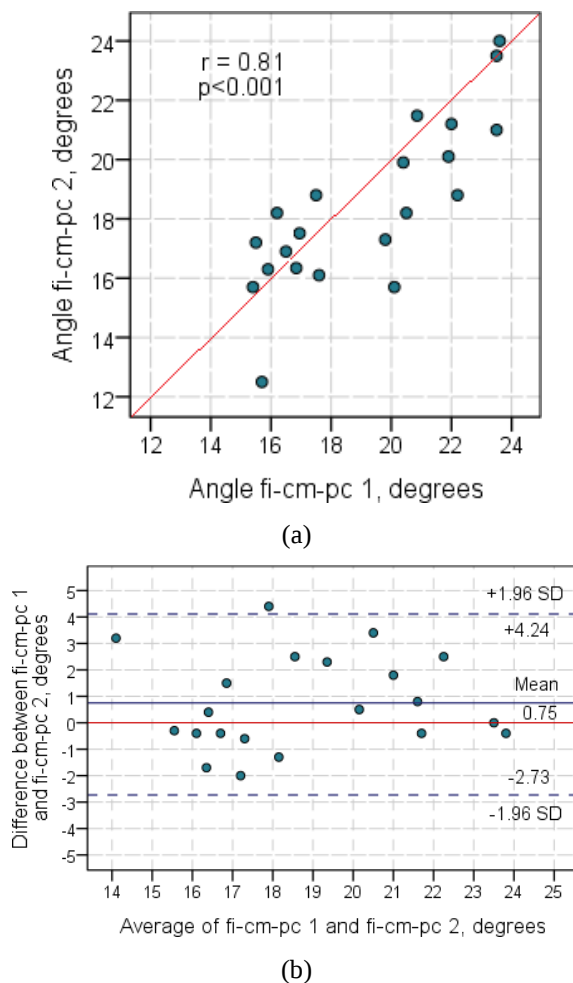


Fig. 5 The accuracy of the fi-cm-pc angle estimates, without and with consideration of the n/h head, is shown in the scatter plot (a) and in the Bland-Altman diagram (b). The red lines indicate the ideal position of the points for complete consistency of the measurements.

Although the accuracy of angle estimation appears to be higher when the mandibular head is absent, it should be noted that the angles examined differ on average by more than a factor of three. When calculating the relative error of measuring these angles without considering the position of the lower jaw head, the results were comparable. For the angle fi-cm-pc the relative error was 3.9% and for msp-cm 4.4%.

We analyzed the absolute values of the differences between two measurements, that is, the deltas. The results (Table 2) show that in about 25% of cases the difference in fi-cm-pc angles is between 2.5 and 4.4 degrees, while in the remaining 75% the differences are smaller. From a clinical point of view, these discrepancies are acceptable. However, larger discrepancies were observed for the msp-cm angle. In the upper quartile, the values range from 7 to 11.3 degrees. The graphical comparison of the estimates for the two angles is shown in the scatter plots and the Bland-Altman plot. For the fi-cm-pc angle (Fig. 5), there is a strong correlation between the measurements ($r = 0.8$, $p < 0.001$), indicating a low systematic error. For the

msp-cm angle, however, the measurements with and without consideration of the position of the n/h head are not correlated ($r = 0.52$, $p = 0.015$) (Fig. 6). In this case, there is a visible systematic error, as the points in the scatter diagram are below the diagonal and the average difference in the Bland-Altman diagram is 3.1 degrees. Nevertheless, the scatter in both diagrams is random and not dependent on the angles themselves which indicates that there is no trend. To correct the error in the msp-cm measurements, the 3.1 degree value found could be added back to the results.

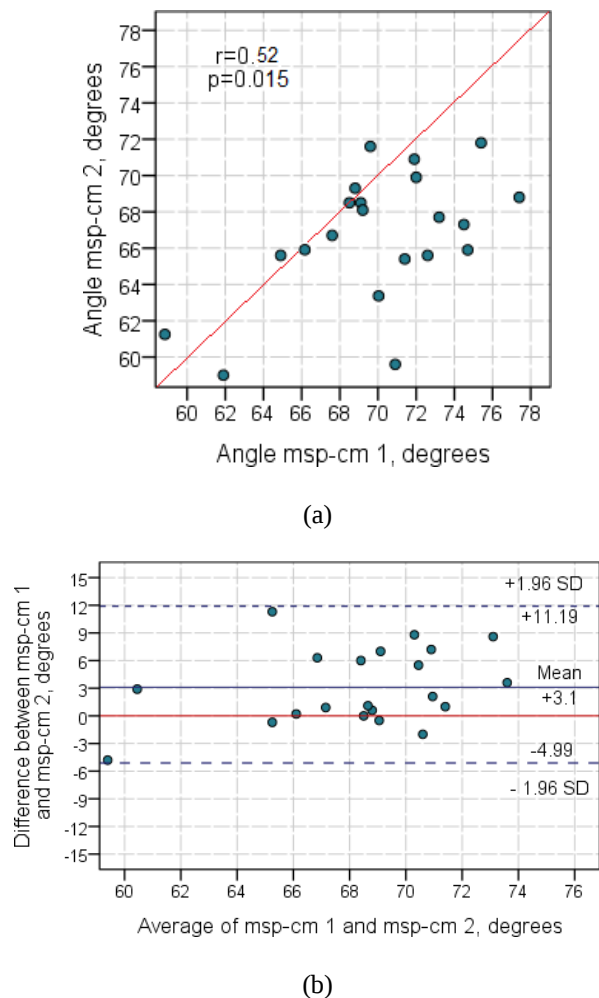


Fig. 6 The accuracy of the MSP-CM angle estimates without considering the lower jaw head compared to considering the head: scatterogram (a) and Bland-Altman plot (b). The red lines indicate the ideal position of the points for complete consistency of the measurements.

4 Discussion

The TMJ is one of the most complex joints of the human skeleton, allowing articular, rotational and translational movements of the mandible [15, 16]. This fact explains the wide spectrum of clinical manifestations of anatomical and functional disorders of the TMJ. Together with the muscles that surround it, the TMJ determines the type of jaw movements and the quality of tooth contact

and influences the ability to produce speech. The TMJ consists of several anatomical structures, and clinical variables can alter its morphology and position through remodeling or surface changes as an adaptive response [17]. In a study by Ahmad et al. [18], it was found that changes in TMJ structures during tooth eruption, permanent dentition formation and tooth loss can be reliably detected clinically and confirmed using CBCT. This fact should be taken into account when planning the treatment and determining the time period for its implementation. These changes in the shape and position of the TMJ in the mandibular fossa may therefore represent an anatomical variation or a functional response to developmental events or an independent pathological condition.

All this leads to continuous improvement of existing methods and the development of new techniques for the diagnosis of TMJ disorders. These techniques include methods for visualizing the bony and soft tissue structures of the TMJ and head, as well as the use of 3D technologies.

In the modern context, additive technologies are based on approaches that allow us not only to visualize an object, but also to position it correctly in 3D space in relation to other structural and functional elements of the skull. To fulfill these requirements, methods for positioning and navigating 3D objects based on craniometric points identified on X-ray images are used.

Therefore, the development of methods to recognize craniometric points on X-ray images of the TMJ to create a bioengineered structure and navigate it during installation in the patient's bed is a promising area of research in transplantology and regenerative medicine.

Currently, the most appropriate diagnostic method for this purpose is CBCT, which allows visualization of the bony structures of the TMJ and planning for 3D reconstruction of the area [19–21].

García-Sanz et al. [22] have shown that CBCT is an accurate and reliable method for both volumetric and linear measurements of the TMJ structures. It was developed specifically for the visualization of structures in the oral and maxillofacial region. The accuracy of linear measurements with CBCT is within 0.3 millimeters which is sufficient for accurate and reliable clinical examinations. This allows precise linear and angular measurements to be made in the craniofacial complex, even in the presence of soft tissue [23].

Another study by Frongia et al. [24], performed on 28 dry skulls, has shown that changing the orientation of the skull during image acquisition do not significantly affect the accuracy of linear measurements. However, given the small intra-articular spaces of the TMJ and the importance of the collected data for the final diagnosis, several factors should be considered both during and after three-dimensional (3D) data acquisition. These include the type of CBCT scanner, the head position, the realignment of the skull after segmentation, the field of view, and the reliability and repeatability of the identification of reference slices for the measurements.

In this context, based on the specific requirements of Zhang et al. [25] and the data from the present study, it should be noted that the realignment (or positioning of the skull region of interest in 3D space) should be performed along planes constructed by craniometric points inscribed in the region of interest on the anatomical radiograph. A craniometric point fulfills the criteria of reliability and repeatability defined by Zhang et al. The position of the TMJ in the mandibular fossa is an important factor in the diagnosis and planning of orthognathic surgery [26]. Any errors in this analysis can lead to recurrence or later complications [27]. In the era of three-dimensional (3D) diagnostics, direct analysis of the condylar position is essential, as the three-dimensional stability of mandibular movements is influenced by the temporomandibular joint position. Determining the anatomical relationship between the facial bones and the temporomandibular joint enables the planning of orthodontic treatment to correct the occlusion in different occlusal positions [28–30].

Most adolescent orthodontic patients usually stop treatment before the TMJ has completed its maturation. Since occlusion can strongly influence the condylar axis [31], determining its displacement in three-dimensional space is of utmost importance [32]. Traditional radiographic examination methods do not provide accurate and valuable information in this regard [33, 34]. Therefore, mandibular position indicators (MPI) and other similar tools have been introduced to quantify the three-dimensional displacement of the condylar axis [35–37]. The study by M. J. Ponces et al. [38] clearly shows that in patients with a hyperdivergent facial pattern, the risk of misdiagnosis of an orthodontic case is about 30% if the condylar position is not assessed in 3D positions. This is because cephalometric measurements (ANB, Sgo/NMe and SN-ML) do not provide enough information to predict the frequency, magnitude and direction of displacement of the LFG at the level of the condyles. Modern algorithms for automatic segmentation of the mandibular head and visualization of the measured cortical layer thickness in the form of a three-dimensional model with a color map facilitate the automated quantitative assessment of bone thickness changes of the temporomandibular joint complex during CBCT [39]. Quantification of morphologic changes in the condyle requires the creation of a 3D model by segmentation of volumetric images, such as computed tomography (CT) [40]. Volumetric segmentation can be performed manually, semi-automatically or fully automatically. However, manual or semi-automatic segmentation requires extensive training to achieve accurate segmentation of the condyle, as it is difficult to distinguish the condylar head from the joint fossa due to the low bone density in the TMJ region and the lack of contrast, especially in low-dose CT images. Images such as cone-beam CT (CBCT) can be used [41]. Ham et al. have proposed automatic segmentation of four components, namely cranial hard tissue, maxillary sinus, mandible and mandibular canals, in CBCT images of the

face using a 3D U-mesh architecture [42]. However, the mandibular segmentation model presented was for the entire mandible, so the segmentation results in the condylar region were not accurate for analytical purposes. To address this, Y. Liu et al. [43] developed an algorithm to automatically segment the mandibular condyles using a 3D U-mesh. They performed a stress test to determine the optimal dataset size for model development and combined a modified U-mesh with an ultra-precise neural network to create a segmentation model that can classify target regions for 3D TMJ modeling [44].

5 Conclusions

The preservation of the anatomical and functional integrity of the TMJ is a crucial factor for the success of reconstructive surgical procedures. The data presented show that the method of determining the position of the mandibular condyle both in the presence and absence of a mandibular head is very effective when using craniometric calculations. This approach enables accurate determination of the position of the condyle and the creation of an accurate model for biomechanical design and endoprosthetic fabrication.

In addition, the use of the craniometric methodology avoids errors in the calculation of the condyle position, leading to more precise and durable results. Consequently, this technique proves to be a valuable tool

for oral surgeons and dentists when it comes to precisely locating the mandibular condyle during surgical procedures.

Craniometric points and indices were determined to analyze the X-ray anatomical images of the skull bones taken with CBCT in axial projection. These data are used in the 3D modeling of the bioengineered mandibular head and branch construction.

Stable relationships were identified between the craniometric indices that allow the position of the mandibular head within the mandibular fossa of the temporal bone to be determined. These relationships also apply when the mandibular fossa is not present.

When modeling the mandibular head, it is important to note that its medial sagittal plane is offset by a certain angle from the medial sagittal plane of the mandibular branch.

For the correct design and placement of the 3D-printed mandibular head prosthesis, stable cranial measurements of the medial sagittal plane and the frontal plane were taken, which enabled the placement of the prosthesis in the mandibular fossa of the temporal bone and the subsequent correct fixation of the mandibular branch.

Disclosures

The authors declare that they have no conflict of interest.

References

1. S. Barghan, S. Tetradis, and S. Mallya, “[Application of cone beam computed tomography for assessment of the temporomandibular joints](#),” *Australian Dental Journal* 57(s1), 109–118 (2012).
2. A. Hunter, S. Kalathingai, “[Diagnostic Imaging for Temporomandibular Disorders and Orofacial Pain](#),” *Dental Clinics of North America* 57(3), 405–418 (2013).
3. B. Krishnamoorthy, N. Mamatha, and V. Kumar, “[TMJ imaging by CBCT: Current scenario](#),” *Annals of Maxillofacial Surgery* 3(1), 80–83 (2013).
4. M. Jaber, A. Khalid, A. Gamal, R. Faisal, A. Mathew, and M. Ingafou, “[A Comparative Study of Condylar Bone Pathology in Patients with and without Temporomandibular Joint Disorders Using Orthopantomography](#),” *Journal of Clinical Medicine* 12(18), 5802 (2023).
5. E. A. Bulychева, “Differentiated approach to the development of pathogenetic therapy of patients with temporomandibular joint dysfunction complicated by hypertonia of masticatory muscles,” MD Thesis Abstract, Pavlov University, Saint Petersburg (2010). [in Russian]
6. I. S. Naidanova, “Features of functional disorders of temporomandibular joint and masticatory muscles in young patients with preserved tooth rows,” MD Thesis Abstract, Chita (2020). [in Russian]
7. V. P. Potapov, Etiology, pathogenesis, diagnosis and complex treatment of patients with diseases of temporomandibular joint caused by violation of functional occlusion: a monography, Pravo, Samara (2019). ISBN: 978-5-6041835-5-7. [in Russian]
8. A. Y. Drobyshev, Diseases of temporomandibular joint, GEOTAR-Media, Moscow (2022). ISBN: 978-5-9704-6079-5. [in Russian]
9. D. A. Domenyuk, B. N. Davydov, S. V. Dmitrienko, A. V. Lepilin, and I. V. Fomin, “[Diagnostic possibilities of cone-beam computed tomography in craniomorphological and craniometric studies in the assessment of individual anatomical variability \(Part III\)](#),” *Institute of Dentistry Scientific and Practical Journal* 2(83), 48–53 (2019). [in Russian]
10. S. M. Fantini, J. B. Paiva, J. Rino Neto, G. C. Dominguez, J. Abrão, and J. W. Vigoritto, “[Increase of condylar displacement between centric relation and maximal habitual intercuspation after occlusal splint therapy](#),” *Brazilian Oral Research* 19(3), 176–182 (2005).

11. T. Baccetti, L. Franchi, and J. A. McNamara, “[The Cervical Vertebral Maturation \(CVM\) Method for the Assessment of Optimal Treatment Timing in Dentofacial Orthopedics](#),” *Seminars in Orthodontics* 11(3), 119–129 (2005).
12. S. Sokhn, R. Challita, A. Challita, and R. Challita, “[The Infraorbital Foramen in a Sample of the Lebanese Population: A Radiographic Study](#),” *Cureus* 11(12), e6381 (2019).
13. D. Nanayakkara, R. Peiris, N. Mannapperuma, and A. Vadysinghe, “[Morphometric Analysis of the Infraorbital Foramen: The Clinical Relevance](#),” *Anatomy Research International* 2016, 917343 (2016).
14. O. V. Slesarev, “[Clinical and diagnostic substantiation of methodology and principles of interdisciplinary approach in the treatment of patients with temporomandibular disorders](#),” MD Thesis Abstract, Samara State Medical University (2020). [in Russian]
15. X. Alomar, J. Medrano, J. Cabratosa, J. A. Clavero, M. Lorente, I. Serra, J. M. Monill, and A. Salvador, “[Anatomy of the Temporomandibular Joint](#),” *Seminars in Ultrasound, CT and MRI* 28(3), 170–183 (2007).
16. D. A. Domenyuk, E. G. Vedeshina, and S. V. Dmitrienko, “[The use of craniometric and morphological studies in the assessment of structural elements of the temporomandibular joint](#),” *Kuban Scientific Medical Bulletin* 1(1), 33–40 (2017). [in Russian]
17. F. Lobo, E. D. S. Tolentino, L. C. V. Iwaki, L. Â. Walewski, W. M. Takeshita, and M. Chicarelli, “[Imaginology Tridimensional Study of Temporomandibular Joint Osseous Components According to Sagittal Skeletal Relationship, Sex, and Age](#),” *Journal of Craniofacial Surgery* 30(5), 1462–1465 (2019).
18. M. Ahmad, L. Hollender, Q. Anderson, K. Kartha, R. Ohrbach, E. L. Truelove, M. T. John, and E. L. Schiffman, “[Research diagnostic criteria for temporomandibular disorders \(RDC/TMD\): development of image analysis criteria and examiner reliability for image analysis](#),” *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology* 107(6), 844–860 (2009).
19. O. B. Honey, W. C. Scarfe, M. J. Hilgers, K. Klueber, A. M. Silveira, B. S. Haskell, and A. G. Farman, “[Accuracy of cone-beam computed tomography imaging of the temporomandibular joint: Comparisons with panoramic radiology and linear tomography](#),” *American Journal of Orthodontics and Dentofacial Orthopedics* 132(4), 429–438 (2007).
20. L. I. Peltonen, A. A. Aarnisalo, M. K. Kortensniemi, A. Suomalainen, J. Jero, and S. Robinson, “[Limited cone-beam computed tomography imaging of the middle ear: a comparison with multislice helical computed tomography](#),” *Acta Radiologica* 48(2), 207–212 (2007).
21. C.-K. Min, K.-A. Kim, K.-E. Lee, B.-J. Suh, and W. Jung, “[A study on volumetric change of mandibular condyles with osteoarthritis using cone-beam computed tomography](#),” *Scientific Reports* 14(1), 10232 (2024).
22. V. García-Sanz, C. Bellot-Arcís, V. Hernández, P. Serrano-Sánchez, J. Guarinos, and V. Paredes-Gallardo, “[Accuracy and Reliability of Cone-Beam Computed Tomography for Linear and Volumetric Mandibular Condyle Measurements. A Human Cadaver Study](#),” *Scientific Reports* 7(1), 11993 (2017).
23. R. Ma, S. Yin, and G. Li, “[The detection accuracy of cone beam CT for osseous defects of the temporomandibular joint: a systematic review and meta-analysis](#),” *Scientific Reports* 6(1), 34714 (2016).
24. G. Frongia, M. G. Piancino, and P. Bracco, “[Cone-Beam Computed Tomography: Accuracy of Three-dimensional Cephalometry Analysis and Influence of Patient Scanning Position](#),” *Journal of Craniofacial Surgery* 23(4), 1038–1043 (2012).
25. Z. Zhang, J. Cheng, G. Li, J. Zhang, Z. Zhang, and X.-C. Ma, “[Measurement accuracy of temporomandibular joint space in Promax 3-dimensional cone-beam computerized tomography images](#),” *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology* 114(1), 112–117 (2012).
26. G. Muñoz, S. Olate, M. Cantín, B. Vásquez, M. Del Sol, and R. Fariña, “[TMJ in facial class III deformity. Condyle/fossa relations](#),” *International Journal of Clinical and Experimental Medicine* 7(9), 2735–2739 (2014).
27. I. Radej, I. Szarmach, “[The Role of Maxillofacial Structure on Condylar Displacement in Maximum Intercuspal and Centric Relation](#),” *BioMed Research International* 2022, 1–10 (2022).
28. J. P. Okeson, “[Evolution of occlusion and temporomandibular disorder in orthodontics: Past, present, and future](#),” *American Journal of Orthodontics and Dentofacial Orthopedics* 147(5), S216–S223 (2015).
29. S. D. Crawford, “[Condylar axis position, as determined by the occlusion and measured by the CPI instrument, and signs and symptoms of temporomandibular dysfunction](#),” *The Angle Orthodontist* 69(2), 103–114 (1999).
30. P. E. Dawson, “[New definition for relating occlusion to varying conditions of the temporomandibular joint](#),” *The Journal of Prosthetic Dentistry* 74(6), 619–627 (1995).
31. R. H. Roth, “[Functional occlusion for the orthodontist](#),” *Journal of Clinical Orthodontics* 15(1), 32–40 (1981).
32. F. E. Cordray, “[The importance of the seated condylar position in orthodontic correction](#),” *Quintessence International* 33(4), 284–293 (2002).
33. A. G. Pullinger, L. Hollender, W. K. Solberg, and A. Petersson, “[A tomographic study of mandibular condyle position in an asymptomatic population](#),” *The Journal of Prosthetic Dentistry* 53(5), 706–713 (1985).
34. D. C. Hatcher, R. J. Blom, and C. G. Baker, “[Temporomandibular joint spatial relationships: Osseous and soft tissues](#),” *The Journal of Prosthetic Dentistry* 56(3), 344–353 (1986).
35. S. D. Crawford, “[Condylar axis position, as determined by the occlusion and measured by the CPI instrument, and signs and symptoms of temporomandibular dysfunction](#),” *The Angle Orthodontist* 69(2), 103–114 (1999).

36. S. R. Alexander, R. N. Moore, and L. M. DuBois, "[Mandibular condyle position: Comparison of articulator mountings and magnetic resonance imaging](#)," *American Journal of Orthodontics and Dentofacial Orthopedics* 104(3), 230–239 (1993).
37. D. Levine, B. B. Gosink, "[Ultrasound shows changes in postmenopausal pelvis](#)," *Diagnostic Imaging* 14(10), 96–101 (1992).
38. M. J. Ponces, J. P. Tavares, J. D. Lopes, and A. P. Ferreira, "[Comparison of condylar displacement between three biotypological facial groups by using mounted models and a mandibular position indicator](#)," *The Korean Journal of Orthodontics* 44(6), 312–319 (2014).
39. Y. H. Kim, J. Y. Shin, A. Lee, S. Park, S.-S. Han, and H. J. Hwang, "[Automated cortical thickness measurement of the mandibular condyle head on CBCT images using a deep learning method](#)," *Scientific Reports* 11(1), 14852 (2021).
40. L. H. S. Cevidanes, A.-K. Hajati, B. Paniagua, P. F. Lim, D. G. Walker, G. Palconet, A. G. Nackley, M. Styner, J. B. Ludlow, H. Zhu, and C. Phillips, "[Quantification of condylar resorption in temporomandibular joint osteoarthritis](#)," *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology* 110(1), 110–117 (2010).
41. J. Schilling, L. C. R. Gomes, E. Benavides, T. Nguyen, B. Paniagua, M. Styner, V. Boen, J. R. Gonçalves, and L. H. S. Cevidanes, "[Regional 3D superimposition to assess temporomandibular joint condylar morphology](#)," *Dentomaxillofacial Radiology* 43(1), 20130273 (2014).
42. J. J. Kim, H. Nam, N. R. Kaipatur, P. W. Major, C. Flores-Mir, M. O. Lagraverre, and D. L. Romanyk, "[Reliability and accuracy of segmentation of mandibular condyles from different three-dimensional imaging modalities: a systematic review](#)," *Dentomaxillofacial Radiology* 49(5), 20190150 (2020).
43. Y. Liu, Y. Lu, Y. Fan, and L. Mao, "[Tracking-based deep learning method for temporomandibular joint segmentation](#)," *Annals of Translational Medicine* 9(6), 467–467 (2021).
44. N. Jha, T. Kim, S. Ham, S.-H. Baek, S.-J. Sung, Y.-J. Kim, and N. Kim, "[Fully automated condyle segmentation using 3D convolutional neural networks](#)," *Scientific Reports* 12(1), 20590 (2022).