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Evaluating sagittal condylar inclination: a comparative analysis of various digital workflow measures

Yeqing Wang[1], Xin Wang[2], Litong Li[1] and Meng Cao[1*]

Abstract

Introduction This study aims to compare sagittal condylar inclination (SCI) measurements derived from three workflows: intraoral scan (IOS) aligned with cone-beam computed tomography (CBCT), IOS aligned with facial scan (FS), and a jaw motion analyzer (JMA) system, in a cohort of young individuals with established normal occlusion. Additionally, the study aims to identify sources contributing to variance in these measurement approaches.

Methods Twenty-four healthy individuals exhibiting normal occlusion were enrolled in this clinical trial. The SCI was delineated using a virtual articulator (VA) by aligning IOS with both CBCT and FS, creating two distinct workflows labeled CBCT-IOS and FS-IOS, respectively. Concurrently, SCI measurements were also acquired using a JMA. The normality of data distribution for the difference in bilateral SCI measurements within each workflow was tested using the Shapiro-Wilk test. Depending on the outcomes of this test, we utilized either a paired-sample T-test or Wilcoxon test for bilateral SCI comparisons. The inter-workflow differences were assessed using the Kruskal-Wallis H test. Bland-Altman plots were assess the interchangeability and consistency across each pair of digital methods and to evaluate the aggregate consistency among the trio of digital approaches.

Results The analysis revealed that the CBCT-IOS workflow yielded the lowest average SCI measurements, whereas the JMA workflow produced the highest values. No significant differences were found in the SCI measurements between the left and right sides obtained by CBCT-IOS and JMA ($P > .05$), with the exception of the FS-IOS workflow ($P = .002$). Additionally, inter-flow comparisons revealed no significant differences in SCI measurements ($P > .05$), except when contrasting the SCI as measured by CBCT-IOS and JMA ($P = .0131$). The Bland-Altman plots demonstrated a high degree of consistency and 95% limits of agreement across the three digital workflows.

Conclusion SCI measurements obtained from the three digital workflows exhibit a high degree of consistency and are interchangeable, affirming their clinical applicability for precise SCI assessment in young individuals with normal occlusion.

Keywords Sagittal condylar inclination, Virtual articulator, Cone-beam computed tomography, Facial scan, Intraoral scan

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Introduction

The utilization of articulators in dental diagnosis and treatment is an integral aspect of occlusal and mandibular movement analysis. Traditionally, the process involved recording the horizontal and vertical relationships of the patient's dentition and then transferring a plaster cast to a mechanical articulator using a facebow. This workflow is time-consuming and labor-intensive. Additionally, the use of impression materials and facebow placement can cause discomfort to patients, and errors due to gypsum deformation are unavoidable. With advancements in digital oral medicine technologies, such as virtual reality and computer-aided design and therapy, the virtual articulator has emerged as an important tool in many dental software applications [1]. This innovation enhances patient comfort, increases the efficiency of oral therapies, and expands the possibilities of clinical diagnosis and treatment [2, 3]. However, the transition to virtual articulator technology has introduced several challenges. One primary issue concerns transferring multi-source stomatognathic system data to the virtual articulator and obtaining patient-specific parameters.

Ultrasonic jaw tracking devices are widely used in clinical practice and offer a solution to this problem. These devices involve patients wearing sensors on their jaws, with the upper jaw sensor remaining fixed while the lower jaw moves. The spatial position changes of the lower jaw are calculated based on signal source time variations, enabling the recording of condylar and incisor motion trajectories and articulator parameter acquisition. This method has been reported to be easy to implement, clinically accurate, and exhibit high sensitivity. However, it fails to fully replicate the neural regulation and muscle tension involved in human jaw movement, raising questions about the repeatability and reliability of the results [4]. Additionally, combining cone-beam computed tomography (CBCT) with intraoral scans (IOS) has been shown by several studies to accurately, reliably and stably obtain articulator parameters for clinical diagnosis and treatment [5–8]. This method precisely locates individual condylar locations but raises concerns due to the radiation exposure from CBCT scans, which may be unnecessary for some patients. To address this, we proposed aligning three-dimensional facial scans (FS), instead of CBCT, with IOS to acquire articulator parameters. Studies have investigated the alignment of FS with IOS of maximal intercuspal and protrusive interocclusal records to derive articulator parameters [9, 10]. However, there is a paucity of studies comparing the accuracy of this FS-IOS alignment with other digital methods. To address this gap, our study critically evaluates the accuracy of articulator parameters as measured by CBCT-IOS, FS-IO, S and JMA methods.

The selection of a parameter for accuracy comparison in varied workflows is critical. In traditional procedures utilizing the mechanical articulator, an average sagittal condylar inclination of 30° and a transversal condylar of 15° are commonly adopted [11]. However, empirical evidence suggests that utilizing these averages may lead to significant discrepancies: approximately 16% of patients exhibited an error greater than 200 μm at the second molar, and 6% showed errors surpassing 300 μm [12]. Among the articulator parameters, such as Bennett Angle, immediate side shift, and incisal guidance inclination, condylar inclination has been identified as the most influential in dynamic occlusion [13]. It directly impacts the mandibular movement trajectory and the occlusal morphology of teeth, notably the cusp inclination. Anomalies in cusp inclination, whether excessively small or large, are known to precipitate occlusal trauma, potentially resulting in sustained damage to the temporomandibular joint area, manifesting as pain, limited mouth opening, and even structural lesions [14, 15]. Consequently, this trial was designed to compare the sagittal condylar inclination (SCI) as measured by CBCT-IOS, FS-IOS and JMA, and to analyze the sources of discrepancies in these measurements.

Materials and methods

This study was approved by the Medical Ethics Committee of the Third Affiliated Hospital of the Fourth Military Medical University (IRB-REV-2022193). Prior to participation, written informed consent was obtained from each participant. Each of the three workflows was performed on all patients. The study enrolled 24 individuals aged 18–60 of either gender, each of whom met the following inclusion criteria: complete maxillary and mandibular dentition (excluding third molars), broadly symmetrical maxillofacial development, absence of facial or orbital injuries, normal anatomical appearance of the ear, orderly arrangement of the posterior dental cusps with normal anterior dental overlaps, absence of multi-tooth fillings or extensive prostheses, stable maximal intercuspal position, no history of temporomandibular joint disease or trauma, no history of orthodontic treatment, and healthy periodontal tissue.

The SCI was measured using three distinct workflows, each conducted by the same experienced operator. In the CBCT-IOS workflow, an intraoral scanner (Trios 3; 3Shape, Copenhagen, Denmark) captured both dentitions and interocclusal records in maximum intercuspal position (MIP) and protrusive interocclusal position (PIP), saving the data as standard tessellation language (STL) files. Concurrently, each individual underwent a CBCT scan in MIP, covering both dental arches and the TMJ with a field of view (FOV) of 170 mm × 10 mm, with the scan data saved as Digital Imaging and Communications in Medicine (DICOM) files. Utilizing YAKE software, the arches and bony structures were reconstructed in 3D by adjusting surface thresholds for bone and enamel, and the reconstructed data were saved as STL files. These files, along with the IOS scan in PIP, were then imported into Geomagic Wrap 2021; software (3D Systems, Morrisville, NC, USA). The "pin" function was used to fix the interocclusal record at the PIP position and establish a coordinate system. The "N-point registration" and "best-fit alignment" functions registered the reconstructed STL file, using the exposed anterior teeth of the maxilla as the registration reference area, to obtain the relative position of the constructed STL file at the MIP position, which was named STL file1. The Frankfort Horizontal (FH) plane was determined by locating both external auditory meatus points and one infraorbital point. The patient's reconstructed STL file was then imported again into Geomagic Wrap, using the same registration functions selecting specific mandibular dentition landmarks as the registration reference area. This step determined the relative position of the skull at the PIP position, named STL file2. STL file1 and STL file2 were then loaded simultaneously to obtain overlapping images of the condyles in two different head positions. Tangential lines were connected to indicate the motion trajectory of the condyle when the mandible moved from MIP to PIP, and linear coordinates were derived. The angle between this line and the FH plane was calculated to obtain the SCI value for each side, and the process was repeated for the other side (Fig. 1).

In the FS-IOS workflow, the initial step involved affixing mark points corresponding to the lowest margin of the orbit onto the overlying skin of each participant. This was crucial for the subsequent positioning of the horizontal FH plane. An intraoral scanner (TRIOS 3; 3Shape, Copenhagen, Denmark) was then used to scan the maxillary and mandibular arches and occlusal records at the MIP. The patient was then instructed to perform a protrusive movement with the incisors in edge-to-edge contact, and the PIP was recorded using the intraoral scanner. Subsequently, a facial scanner (3dMDface; 3dMD Inc., Atlanta, GA, USA) captured 3D facial images of each patient in both the closed-mouth position and in MIP, using cheek retractors for exposure. The Object File Format (OBJ) file of the facial scan with cheek retractors and the STL file of the intraoral scan in PIP were

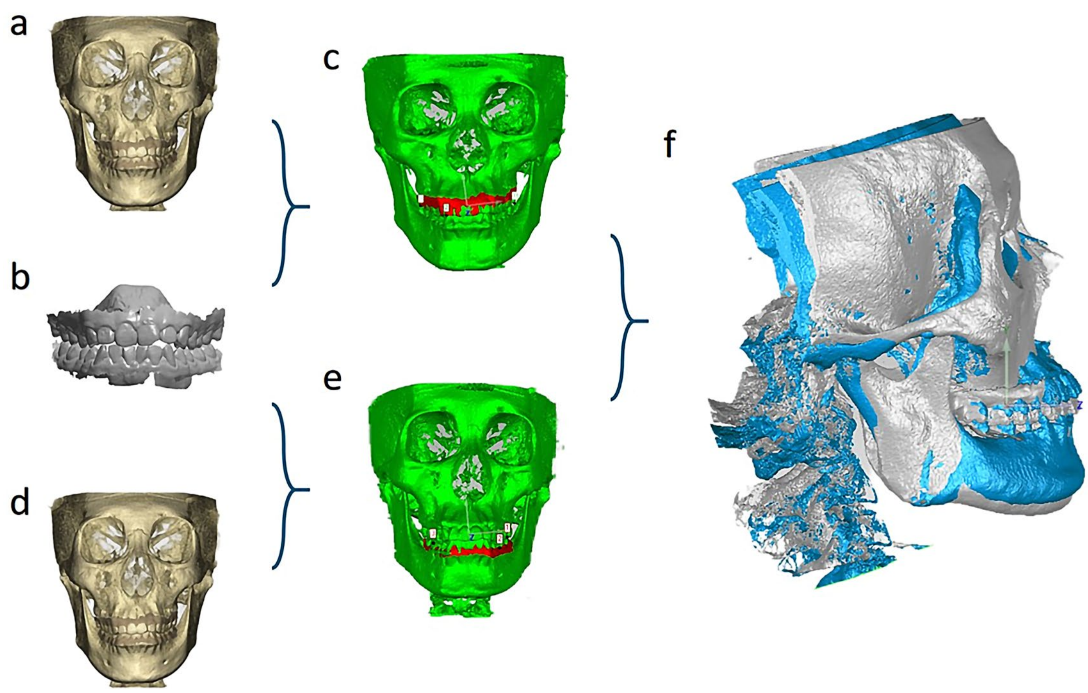

Fig. 1 Registration and analysis process using STL files. The reconstructed STL file of the patient underwent registration with the maxillary and mandibular arches at the PIP, utilizing the exposed anterior teeth as the reference area for alignment. This registration was accomplished via "N-point registration" and "best-fit alignment" functions. (**a**) Reconstructed STL file of the patient's skull. (**b**) IOS image of the patient at the PIP. (**c**) The process of aligning the exposed anterior teeth of the maxillary arch from the patient's skull (as shown in the reconstructed STL file) with the corresponding maxillary dentition in the IOS. The head position achieved after this registration is designated as STL file1. (**d**) Re-import of the reconstructed STL file of the patient's skull for further processing. (**e**) Registration of the exposed anterior teeth of the mandibular arch of the skull (from the reconstructed STL file) with the mandibular dentition in the IOS. The resulting registered head position from this step is named STL file2. (**f**) When STL file1 and STL file2 are loaded concurrently, an overlapped image depicting the two distinct head positions is generated, facilitating a comparative analysis of the mandibular and maxillary orientations in these positions

imported into Geomagic Wrap 2021 software (Research Triangle Park, NC). The FS of the patient using cheek retractors was registered into the IOS in PIP, employing the "N-point alignment" and "best-fit alignment" functions. The exposed anterior teeth of the maxillary arch served as the registration reference area, with the digital dental cast set as a fixed object. This registered FS file was named OBJ file (1) The OBJ file of the FS in the closed-mouth position was then imported into Geomagic Wrap software, where it was registered into the FS using the cheek retractors. The "N-point alignment" and "best-fit alignment" functions were used again, this time using the skin on the forehead as the registration reference area. The FS using the cheek retractors was set as a fixed object. The superior margin of the meatus externa on both sides of this OBJ file was located, and the FH plane was established together with these two landmarks and the right orbitale (Fig. 2). The OBJ file of the FS including the use of cheek retractors was then re-imported into the Geomagic Wrap software and registered into the IOS in PIP. The "N-point alignment" and "best-fit alignment" functions were used with the exposed anterior teeth of the mandibular arch as the registration reference area, setting the IOS in PIP as a fixed object. This file was named OBJ file (2) Concurrently loading OBJ file 1 and OBJ file 2 represented a superimposition of the two positions, as shown in Fig. 3.

Finally, the posterior margin of the tragus of the left ear and its midpoints were located. Connections between the midpoints and the outer canthus of the eyes in OBJ file 1 and OBJ file 2 were established. The center of the outer tragus was set as the center of a sphere with a diameter of 26 mm to construct the sphere. The intersection point of the sphere and the connecting line from the mid-tragus to the outer canthus of the left eye was identified as the left Beyron point (13 mm anterior to the posterior margin of the tragus of the ear on a line from the center of the tragus to the outer canthus of the eye [16]), indicating the location of the hinge axis. A straight line was established by connecting the Beyron point on the left side of OBJ file 1 and OBJ file 2, and the angle between this line and the FH plane was recorded as the left condylar inclination. The same steps were repeated to obtain the right condylar inclination (Fig. 4).

In the JMA workflow, the Jaw Motion Analyzer (Zebris Medical GmbH, Isny, Germany) can be utilized to measure the SCI. The procedure involves affixing a signal receiver to the patient's head and connecting a signal transmitter to a prefabricated metal mandibular fork. This fork is initially bent to conform to the patient's mandibular dentition and aligned parallel to the mandibular occlusal plane. Temporary crown resin is applied to the inner surface of the mandibular fork, which, after solidification and trimming, is re-injected with the resin to securely place the fork in the mouth, using the undercut

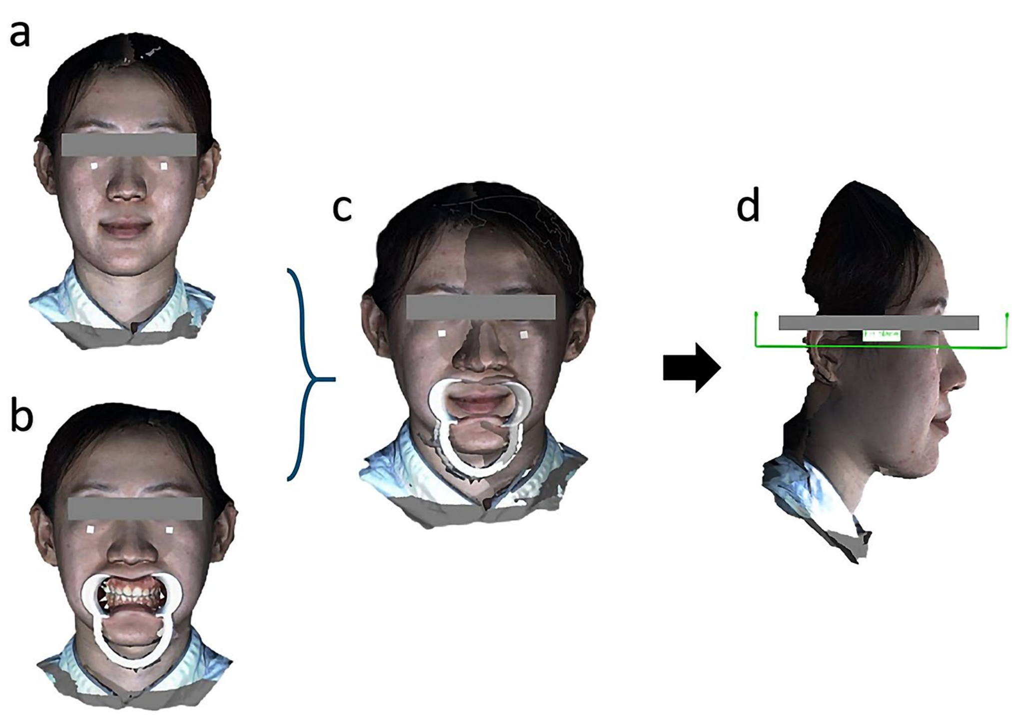

Fig. 2 Locating the FH plane. (**a**) FS image of the patient in a closed-mouth position. (**b**) FS image with cheek retractors in place. (**c**) Superimposition of the FS image in the closed-mouth position over the FS image using cheek retractors, aiding alignment and comparison. (**d**) The establishment of the FH plane, using the superior margin of the meatus externa on both sides and the right orbitale as anatomical landmarks

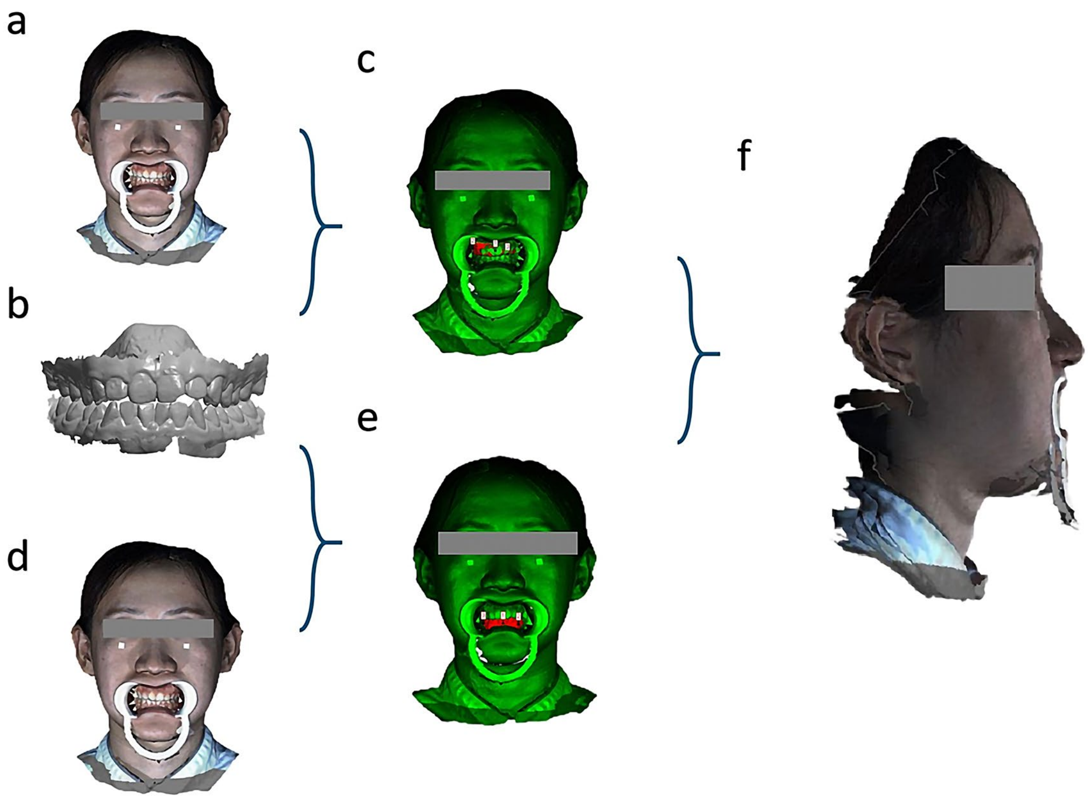

Fig. 3 Registration and superimposition in the FS-IOS workflow. (**a**) FS image of the patient using a cheek retractor. (**b**) IOS image of the patient at the PIP. (**c**) Registration of the exposed anterior teeth of the maxillary arch from the FS with the maxillary dentition in the IOS. The resultant registered head position is designated as OBJ file1. (**d**) Re-importing the FS image with a cheek retractor for further processing. (**e**) Registration of the exposed anterior teeth of the mandibular arch from the FS with the mandibular dentition in the IOS. The head position post-registration is named OBJ file2. (**f**) Overlapping image generated by loading both OBJ file1 and OBJ file2 simultaneously, facilitating comparative analysis of the two different head positions

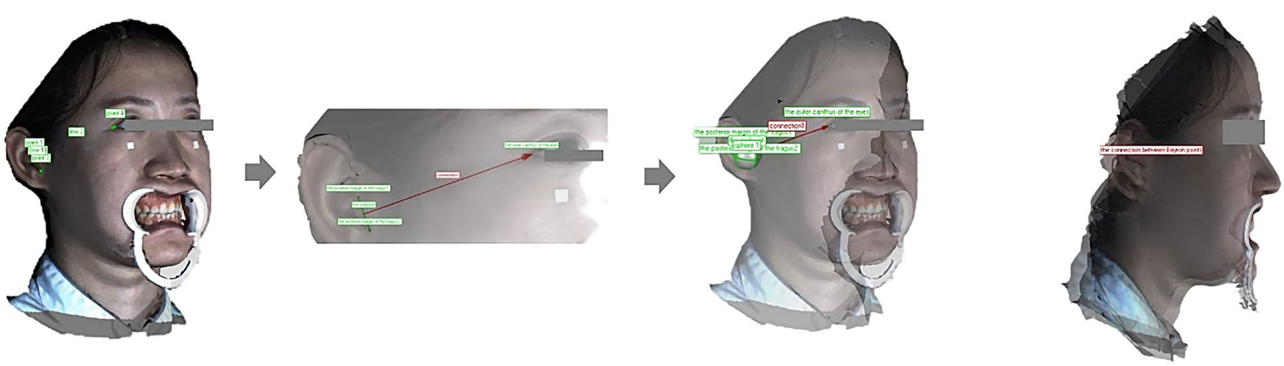

Fig. 4 Identification and connection of Beyron points in facial scans. Displaying the identification and connection of Beyron points in OBJ file1 and OBJ file2, highlighting their alignment across different head positions

of the teeth for stabilization. Once the material has fully solidified, and it is confirmed that there is no occlusal interference during protrusive and lateral movements, the patient is instructed to perform lateral, protrusive, and mouth-opening movements at a constant speed. Both the start and end positions of each movement are at the MIP. Using the Articulator section of the accompanying WinJaw+software (Zebris), the SCI values in different articulator systems are generated. This process is repeated three times for each patient, with the average of these measurements taken as the final SCI value (Fig. 5).

Statistical analyses were conducted using IBM SPSS Statistics software, v.26 (IBM Corp., Armonk, NY, USA). To assess the normality of the data within each workflow, we used the Shapiro-Wilk normality in conjunction with histogram analysis. The results confirmed that the data distributions confirmed normality, thus the paired-sample T-test was selected to compare the SCI values

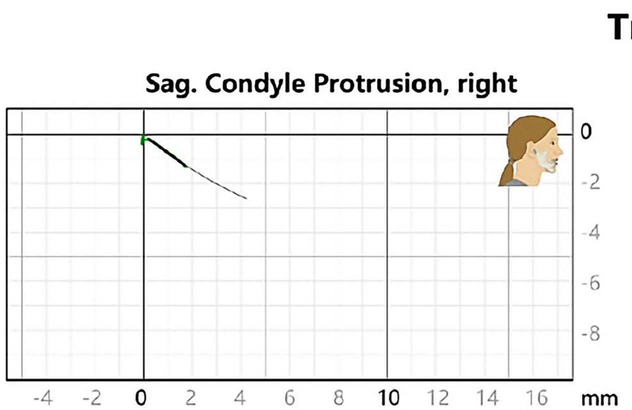

Fig. 5 Bilateral condyle protrusion track recordings

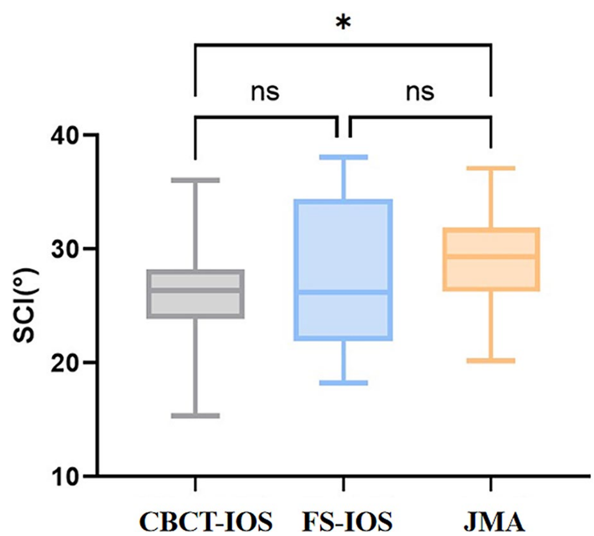

Fig. 6 Boxplots of SCI values for the three workflows. ns, no significance; * $P<.05$; SCI, sagittal condylar inclination; CBCT-IOS, cone-beam computed tomography aligned with intraoral scan; FS-IOS, facial scan aligned with intraoral scan; JMA, jaw motion analyzer

between the left and right sides in each workflow. To compare the SCI values measured by each pair of workflows, we used the Kruskal-Wallis H test. Finally, the clinical consistency of the three measurement methods was evaluated using Bland-Altman plots (GraphPad Prism 9.5; GraphPad Software Inc., La Jolla, CA, USA) (See Fig. 6).

Results

As shown in Table 1, the statistical analysis of SCI measurements obtained from the three workflows revealed some notable differences. The average SCI value measured by CBCT-IOS was found to be the lowest, significantly differing from the values obtained through the other two workflows. In contrast, the JMA recorded the highest average SCI values. SCI values significantly differed within the FS-IOS group (P=.002), but not the CBCT-IOS group and the JMA group. Further analysis utilizing multiple comparisons through the Kruskal-Wallis H test indicated no significant differences between the measurements obtained by CBCT-IOS and FS-IOS, as well as between FS-IOS and JMA. However, a significant difference was observed between CBCT-IOS and JMA, with the latter recording significantly higher SCI values. Additionally, Bland-Altman plots were utilized to test the consistency of different workflows. The plots revealed that the majority of sample points fell within the 95% consistency limit, indicating a high level of agreement between the methods (Fig. 7).

Table 1 Statistical descriptions of SCI values obtained by three workflows

Workflows	Side	Min	Q1	Median	Q2	Max	Mean ± SD	*P*-value
CBCT-IOS	Left	15.36	23.8573	25.2977	27.5162	32.59	25.2947 ± 3.65275	0.740
	Right	19.62	24.1696	26.7238	31.3039	36.06	27.3948 ± 4.61206	
FS-IOS	Left	20.10	21.6408	24.3153	28.5391	37.01	25.9868 ± 5.30575	0.002
	Right	18.26	24.9606	28.5138	35.5001	38.06	29.2268 ± 6.52589	
JMA	Left	20.90	25.1500	29.0500	31.8750	36.30	28.9125 ± 4.28945	0.797
	Right	20.20	26.5750	29.5000	32.0500	37.10	29.3958 ± 3.96567	

CBCT-IOS, cone-beam computed tomography aligned with intraoral scan; FS-IOS, facial scan aligned with intraoral scan; JMA, jaw motion analyzer; Min, Minimum; Q1, first quartile; Max, Maximum; Q3, third quartile; SD, standard deviation. Paired-sample T-test comparing the difference between two sides. Various superscript letters indicate statistically significant differences between the left and right sides ($P<.05$)

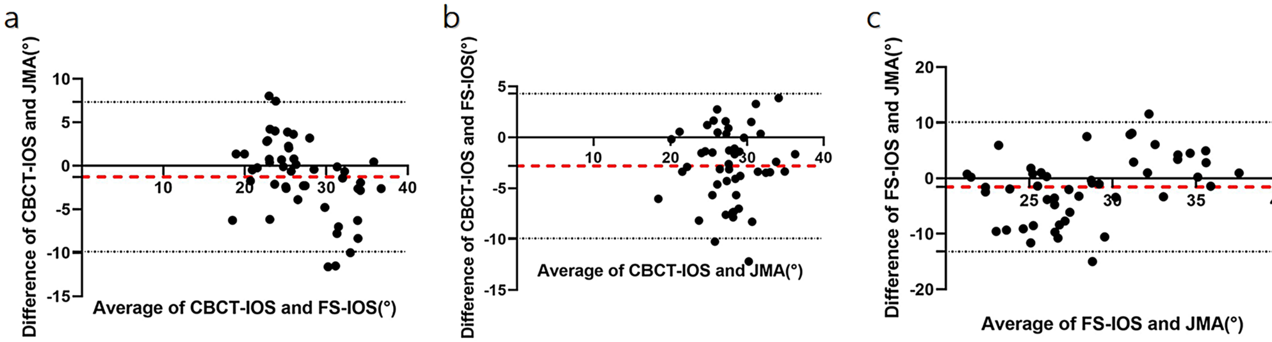

Fig. 7 Bland-Altman plot. (**a**) CBCT-IOS and FS-IOS. (**b**) CBCT-IOS and JMA. (**c**) FS-IOS and JMA

Discussion

Sagittal condylar inclination (SCI) plays a pivotal role in influencing the patient's mandibular movement path and intraoral tooth morphology. Incorrect SCI can result in occlusal interference [17]. Traditionally, SCI values are obtained using a mechanical facebow and occlusal records, a process often marred by material deformations and operator errors, in addition to being time-consuming and labor-intensive. Consequently, various digital workflows for measuring SCI have been developed. This study compared SCI values obtained from three such digital workflows: CBCT-IOS, FS-IOS, and JMA, analyzing the differences between them.

Our findings indicate that average SCI values measured in the CBCT-IOS group were significantly lower compared to FS-IOS. This discrepancy may arise from differences in localizing bone marker points versus skin marker points. In CBCT, the external auditory canal points and infra-orbital points can be accurately localized in bone tissues, while face scans localize only on the soft tissue surfaces, influencing the determination of the FH plane. Moreover, the mandibular movement trajectory in CBCT-IOS is assumed via a tangent line connecting the terminal positions of the condyles in anterior movement, whereas FS-IOS uses the Beyron point as the hinge axis localization point. However, no studies to evaluate the accuracy of the Beyron point and compare it with the commonly used Begstrom point at all and further clinical trials are needed.

In the FS-IOS group, even slight changes in the patient's head position can introduce errors. Therefore, it is crucial to ensure that both the body and head remain still, with no subtle changes in facial expression. This requires us to provide clear instructions and training to patients beforehand and to minimize the time interval between data collections. Additionally, the accuracy of 3D facial imaging devices used in clinical research can significantly impact the precision of subsequent registrations. As digital technology continues to advance and three-dimensional facial scanners become more accurate, the reliability of this method in obtaining SCI will naturally improve.

This study also highlighted that the anatomical characteristics of the posterior oblique plane of the condyle, which primarily determine the anterior extension motion of the condyle in the sagittal direction, affect SCI values. In both the CBCT-IOS and FS-IOS workflows, SCI values were recorded in PIP, possibly not representing the steepest range of the anterior extensor condylar tract. Due to difficulties in accurately simulating the curved condylar guide, a hypothetical straight condylar guide was used, which may have reduced the SCI value, resulting in the highest average SCI value in the JMA group. Notably, Kordaβ [11] and Alshali [18] investigated the amount of anterior extension, concluding that SCI is more stable with a 4–5 mm anterior mandibular extension. Posselt [19] found significant SCI fluctuations within 2 mm of mandibular anterior extension, with no notable difference at 4 mm of anterior extension compared to the PIP. Therefore, due to the high reproducibility and stability of the PIP in daily patient activities, it was selected as the test position for performing the intraoral scan. Using PIP helps avoid the potential errors and mandibular movement trajectory distortions that could arise from the deformation of other occlusal materials used to limit anterior extension. This decision to utilize PIP was integral in aligning the intraoral scan data with information obtained from both the CBCT and the facial scan. However, in the JMA workflow, where the Zebris mandibular movement tracing instrument was employed, the use of intraoral temporary crown resin material posed a challenge. We observed that this material could somewhat alter the normal trajectory of mandibular movements, an aspect that warrants further improvement and investigation in future studies.

When comparing the SCI values of the left and right sides in the same patient, distinct differences emerged in the FS-IOS workflows. This workflow demonstrated significant disparities between the two sides' SCI values. In contrast, the CBCT-IOS workflow and the JMA workflow, revealed no statistically significant difference between the left and right SCI measurements. This consistency in the JMA group is likely attributable to the high reproducibility of the Zebris instrument. As for the CBCT-IOS method, with its precise localization of condylar hard tissue positions on both sides, appeared to be more sensitive to variations in SCI values between the two sides. The use of larger sample sizes in future studies is necessary to deepen our understanding and to make comparisons of these observed differences.

Our findings also revealed that, with the exception of a significant difference observed in the SCI values measured by CBCT-IOS and JMA, there were no significant differences between the SCI values when measured by any two of the methods. Bland-Altman analysis reinforced this observation, demonstrating that each digital method maintained consistency within the 95% limits, suggesting their interchangeability in clinical settings. Notably, the CBCT-IOS workflow is particularly suitable for patients who require or have already undergone CBCT, as it avoids additional radiation exposure and associated costs. Consequently, for patients who do not require CBCT for clinical treatment, the FS-IOS and JMA methods emerge as preferable alternatives, providing accurate SCI values without the need to resort to CBCT scans. Overall, the SCI measurements obtained from the three digital workflows exhibit a high degree of consistency and are interchangeable, affirming their clinical applicability for precise SCI assessment in young individuals with normal occlusion.

There are still some limitations in this clinical research, and several areas warrant further exploration in our future work. First, we could expand the analysis to include additional relevant indicators, such as lateral condylar inclination, immediate lateral movement, and Bennett Angle. Moreover, we did not compare the SCI of patients with different vertical growth patterns or those with maxillofacial or functional asymmetry, which have been shown to affect condylar inclination and other related parameters [20–22]. Lastly, incorporating a wider range of semi-digital and fully digital methods for comparison would enhance the depth and comprehensiveness of the research. These considerations will form the primary focus of our future investigations.

Summary

We found that the SCI values measured using the three digital workflows demonstrated high consistency and can be interchangeably used in clinical settings. This allows clinicians the flexibility to select either the FS-IOS or JMA workflow, both of which avoid radiation exposure, as alternative methods for obtaining SCI values for treatment planning.

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Author contributions
YW: conceptualization and writing original draft; XW: supervision and validation; LL: methodology; MC: review and editing. All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The name of the ethics committee: the Medical Ethics Committee of the Third Affiliated Hospital of the Fourth Military Medical University. The reference number: IRB-REV-2022193.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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