Journal of Cranio-Maxillo-Facial Surgery 51 (2023) 682–691

Contents lists available at ScienceDirect

Journal of Cranio-Maxillo-Facial Surgery

journal homepage: www.jcmfs.com

Anatomical position of the mandibular condyle after open versus closed treatment of unilateral fractures: A three-dimensional analysis

Margje B. Buitenhuis [a], Florine M. Weinberg [a,*], Freek Bielevelt [b], Marjolijn Gilijamse [c], Tymour Forouzanfar [d], Caroline M. Speksnijder [a], Antoine J.W.P. Rosenberg [a]

[a] Department of Oral and Maxillofacial Surgery and Special Dental Care, University Medical Center Utrecht, Utrecht University, Utrecht, the Netherlands
[b] 3D Lab Radboudumc, Radboud University Medical Center, Radboud University, Nijmegen, the Netherlands
[c] Department of Maxillofacial Surgery, OLVG, Amsterdam, the Netherlands
[d] Department of Oral and Maxillofacial Surgery/Oral Pathology, Amsterdam University Medical Centers and Academic Center for Dentistry Amsterdam (ACTA), Vrije Universiteit Amsterdam, Amsterdam, the Netherlands

ARTICLE INFO

Handling editor: Emeka Nkenke

Keywords:
Mandibular condyle
Fracture
Maxillomandibular fixation
Open fracture reduction
Computed tomography

ABSTRACT

This study aimed to compare open and closed treatment for unilateral mandibular condyle neck and base fractures by final three-dimensional (3D) condylar position at 6 months follow-up. 3D position was associated with mandibular functioning and pain. A total of 21 patients received open (n = 11) or closed (n = 10) treatment. 3D positions were assessed on cone-beam computed tomography scans. Volume differences, root mean square, translations, and rotations were obtained related to the pursued anatomical position and compared between treatment groups by the Mann-Whitney *U* test. The 3D position parameters were associated with the maximum interincisal opening (MIO), mixing ability test (MAT), Mandibular Function Impairment Questionnaire (MFIQ), and pain based on Spearman correlation coefficients (r_s). Translation in the medial-lateral direction was smaller after open treatment ($P = 0.014$). 3D position was not associated with the MAT; however, worse position was associated with a smaller MIO. A larger pitch rotation was associated with a worse MFIQ ($r_s = 0.499$, $P = 0.025$). Volume reduction of the affected condyle was associated with more pain ($r_s = -0.503$, $P = 0.020$). In conclusion, after unilateral condylar fractures, worse 3D position is associated with a smaller mouth opening and worse patient-reported outcomes. This is independent of the chosen treatment, despite a better anatomical reduction after open treatment.

1. Introduction

The best treatment strategy for unilateral mandibular condylar fractures remains controversial. The main treatment options are open treatment involving surgical open reduction with internal fixation or closed treatment by maxillomandibular fixation. Both treatment strategies aim primarily to restore mandibular functioning and esthetics (Cavalcanti et al., 2021; Montazem and Anastassov, 2009). In addition, the reduction of pain and complications is pursued. The restoration of mandibular functioning usually comprises the recovery of the anatomical relationship of the fracture segments and dental occlusion (Fonseca et al., 1991; Li et al., 2019).

Therefore, the question arises as to whether the anatomical relationship of the condylar fracture segments differs after open or closed treatment. It is expected that the anatomical relationship would be better after open treatment, since an anatomical reduction of the fractured condyle is possible (Danda et al., 2010; Shiju et al., 2015). However, fixation of the condyle in a non-anatomical position could lead to degenerative joint changes (Devireddy et al., 2014). On the other hand, closed treatment is often associated with a potential for ankylosis and internal derangement of the temporomandibular joint (Al-Moraissi and Ellis, 2015; Han et al., 2020).

The anatomical relationship after treatment can be indicated by the position and morphology of the affected condyle compared to the contralateral healthy condyle. Conventionally, panoramic radiographs have been preferred for diagnosis and follow-up after trauma. However, the 3-dimensional (3D) position of the fractured condylar segment cannot be evaluated on panoramic films. Computed tomography (CT) is a well-established imaging modality with the ability to assess the post-treatment healing pattern of condylar fractures (Du et al., 2021; Singh

* Corresponding author.
E-mail address: f.m.weinberg@umcutrecht.nl (F.M. Weinberg).

https://doi.org/10.1016/j.jcms.2023.09.013
Received 18 July 2022; Received in revised form 24 August 2023; Accepted 30 September 2023
Available online 6 October 2023

et al., 2022).

The anatomical position and healing morphology of fractured condyles affect mandibular functioning and pain (Singh et al., 2022). Mandibular functioning has already been compared between open and closed treatment, presenting conflicting results (Cabral et al., 2020; Rozeboom et al., 2018). Objective functional outcomes involve the maximum mouth opening and masticatory performance, and a patient-reported outcome (PRO) of mandibular functioning is the masticatory ability. In addition, ambiguous results are reported for comparison of open and closed treatment because of experienced pain (Cabral et al., 2020; Shiju et al., 2015). Therefore, it is important to know to what extent the anatomical position of the affected condyle is associated with mandibular functioning and pain.

To the best of our knowledge, there are no clinical studies that compare the 3D position and morphology of unilateral fractured mandibular condyles after open and closed treatment and that relate these findings with both objective functional outcomes and PRO (Kommers et al., 2013). Objectifying differences or similarities in anatomy and studying its association with mandibular functioning and pain might be helpful in the ongoing dilemma of treatment decision making.

Therefore, the first aim was to analyze and compare the final position of the initially fractured mandibular condyle following open and closed treatment of unilateral fractures. The second aim was to evaluate the association between the final position of the affected condyle and mandibular functioning and pain. In addition, this study aimed to classify and compare the morphology of the condyle following open and closed treatment over time.

2. Materials and methods

2.1. Patients

Between January 2017 and November 2019, consecutive patients with unilateral neck or base fractures of the mandibular condyle were asked to participate in this two-center controlled clinical trial at University Medical Center Utrecht (UMCU) and OLVG in the Netherlands. Patients who participated had to be diagnosed with a unilateral neck or base fracture of the mandibular condyle, according to the Arbeitsgemeinschaft für Osteosynthesefragen craniomaxillofacial (AOCMF) classification (McLeod and Keenan, 2021; Neff et al., 2014), with displacement and with or without other fractures of the mandible and with objective malocclusion. Patients had to be aged 18 years or older. Patients were excluded in case of 1) predictable asymmetry of the condyles, 2) a contraindication to general anesthesia, 3) mid-face fractures, 4) insufficient reading or writing skills of the Dutch language, 5) legal incapability, 6) a psychiatric disorder, or 7) pregnancy.

Patients were treated according to the hospital protocols. Patients at UMCU received open treatment, including extraoral open reduction and internal fixation of the fracture by a pre-auricular or retromandibular approach (Handschel et al., 2012). This was combined with bone screws with loose elastic guiding for 2 weeks post-operatively. Patients at OLVG received closed treatment by maxillomandibular fixation with bone screws with tight elastic fixation for 2 weeks, followed by guiding elastics for 4 weeks.

This study was conducted according to the principles of the Declaration of Helsinki (World Medical, 2013) and the Medical Research Involving Humans Subjects Act (WMO). The research protocol was approved by the Ethics Committees of the UMCU (NL59658.041.16). Written informed consent was obtained from all participants.

2.2. Data collection

Age, sex, other mandibular fractures, trauma to treatment interval, occluding units (OU) and whether the patient had a denture (yes/no) were prospectively collected. The number of OU were assessed as the functional units of the patients' natural dentition in the premolar and molar region (range 0–12), where an occluding pair of premolars counts for 1 and an occluding pair of molars counts for 2. All patients received a CT or cone-beam computed tomography (CBCT) scan before treatment, and within 2 weeks and 6 months after the start of the treatment. These scans were used to assess the final position and to classify the morphology of the affected condyle. In addition, mandibular functioning and pain were evaluated 6 months after the start of the treatment.

2.3. CT scans

All patients received a CT scan on which the condylar fracture was diagnosed. A second CT scan was made to evaluate the direct effect of the treatment within 2 weeks after treatment. This scan was preferably a CBCT scan; however, a CT scan was performed if a patient was unstable. A follow-up CBCT scan was retrieved to evaluate the final status of the affected condyle 6 months after the start of the treatment. These CBCT scans were captured with the i-CAT 17-19™ (Imaging Sciences International LLC, Hatfield, PA, USA), VGi EVO (NewTom, Imola, Italy), and Pax Zenith 3D systems (VATECH, Hwaseong-si, South Korea). Voxel size was set 0.3 or 0.4 mm, independent of the CBCT system, and field of view was set to capture the whole mandible including both condyles. The follow-up CBCT scans were used for the 3D analysis of the final position of the affected condyle to evaluate whether the desired anatomical position was achieved.

2.4. Data processing of CBCT scans

2.4.1. Segmentation

Digital Imaging and Communications in Medicine (DICOM) data from follow-up CBCT scans were imported into Mimics (Version 24.0, Materialise, Leuven, Belgium) for semi-automatic segmentation of the mandible. At first, a reduced scatter filter was applied to reduce metal artifacts. Next, bone tissue was segmented by thresholding based on grayscale levels (Fig. 1a). Manual post-processing of the segmentation mask was necessary to achieve accurate bone representation of the condyle. Manual segmentation was performed on a few slices and subsequently auto-interpolated between these slices. Surgical plates and screws were manually excluded (Fig. 1b–c). Subsequently, the segmentation mask was transformed into a 3D object using interpolation to acquire continuity between voxels (Fig. 1d). Finally, the object was smoothed by manual fine-tuning of irregularities and automatic global smoothing (Fig. 1e).

2.4.2. Registration

3D objects of the mandible were further processed in 3-Matic (version 16.0, Materialise, Leuven, Belgium) to enable the comparison of the 3D positions of the affected condyle to the contralateral healthy condyle. First, the 3D object was duplicated and mirrored over the sagittal midplane, resulting in two objects: 1) the original mandible focusing on the healthy condyle, and 2) the mirrored mandible concentrating on the affected condyle. The mirrored mandible was automatically globally aligned with the original mandible (Fig. 2a–b). Next, regions for refined registration were selected on both objects. This was achieved by manual annotation of landmarks, which were used for the automatic creation of planes that defined the borders of the selected region. The following landmarks were selected: the lowest point of the sigmoid notch (Sn) of both mandibular sides, gonion (Go) of both mandibular sides, and the most posterior point of the healthy condylar head (Co). The posterior ramus plane was defined as the plane through both Go-landmarks and the Co-landmark. Perpendicular to this posterior ramus plane and through both Sn-landmarks, the sigmoid notch plane was defined. The sigmoid notch plane marked the superior border of the region for registration. The anterior border was set by the parallel ramus plane, which was the plane parallel to the posterior ramus plane through

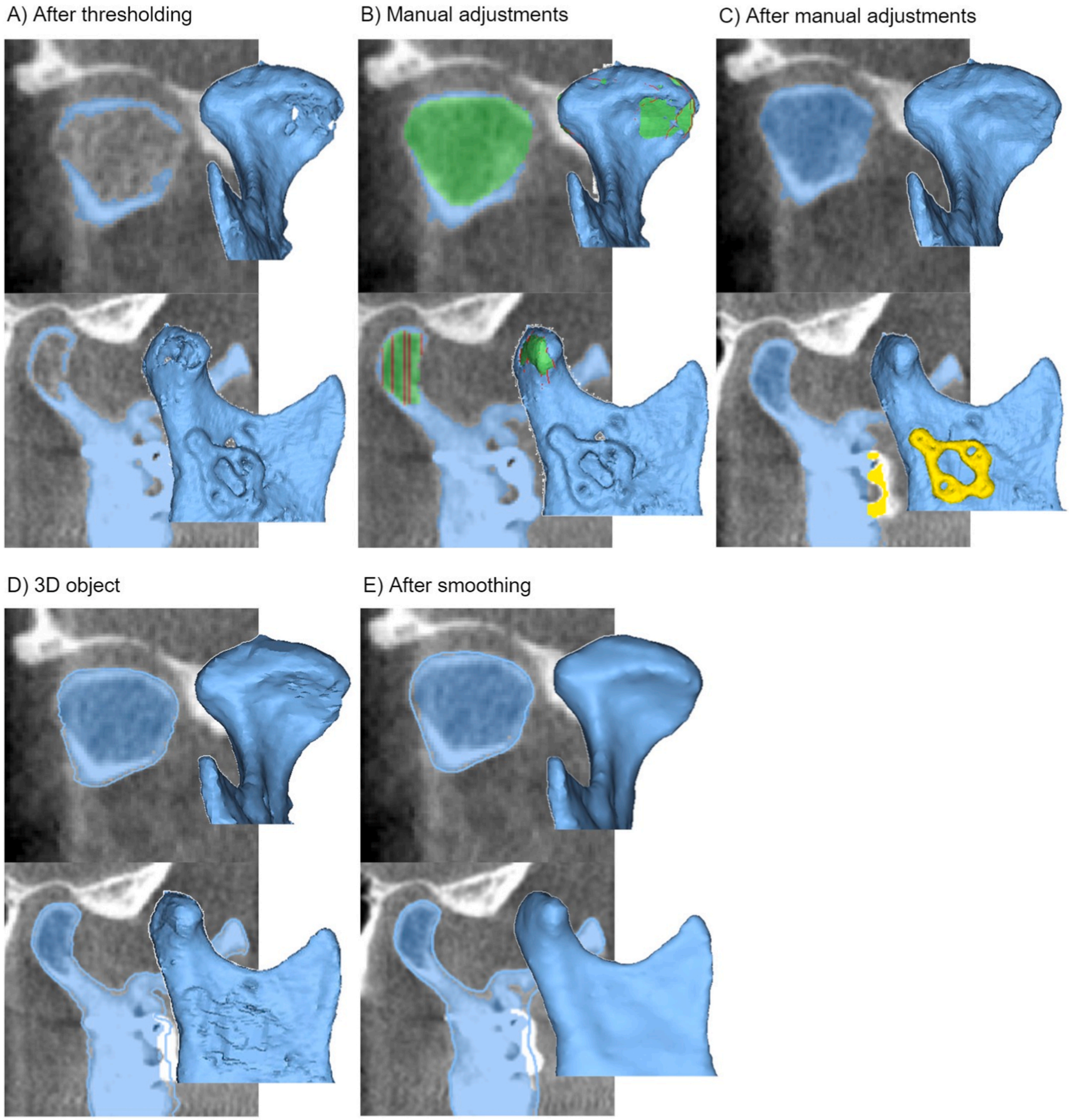

Fig. 1. Semi-automatic segmentation of the mandible. A. mask after thresholding; B. manual correction (red) with automatic interpolation (green); C. mask after manual corrections, also excluding surgical plates screws (yellow); D. conversion of the mask to 3D object; E. 3D object after semi-automatic smoothing.

the Sn-landmark of the side of interest. The inferior and posterior borders of the region for registration followed the edge of the mandible (Fig. 2c). Based on these selected regions, the mirrored mandible object was registered to the original mandible object with the iterative closest point (ICP) algorithm (Fig. 2d). This resulted in a refined overlay of affected and healthy sides of the mandible, enabling the comparison of the 3D positions of the affected and healthy condyles (Fig. 2e).

2.4.3. *3D position*

To compare both condyles, the (absolute) volume difference, the root mean square (RMS) of the distances, translation, and rotation were determined. The inferior border of both condyles was defined by the sigmoid notch plane. The volume difference was determined by subtracting the volume of the healthy condyle from the volume of the affected condyle in 3-Matic. Absolute volume differences were also calculated, to indicate the overall differences between both condyles. Next, the signed Euclidean distance was calculated from the affected condyle to the closest point of the healthy condyle in 3-Matic (Fig. 2f). The RMS of these distances was calculated by first squaring the distances, then taking the mean, and finally neutralizing the squaring by

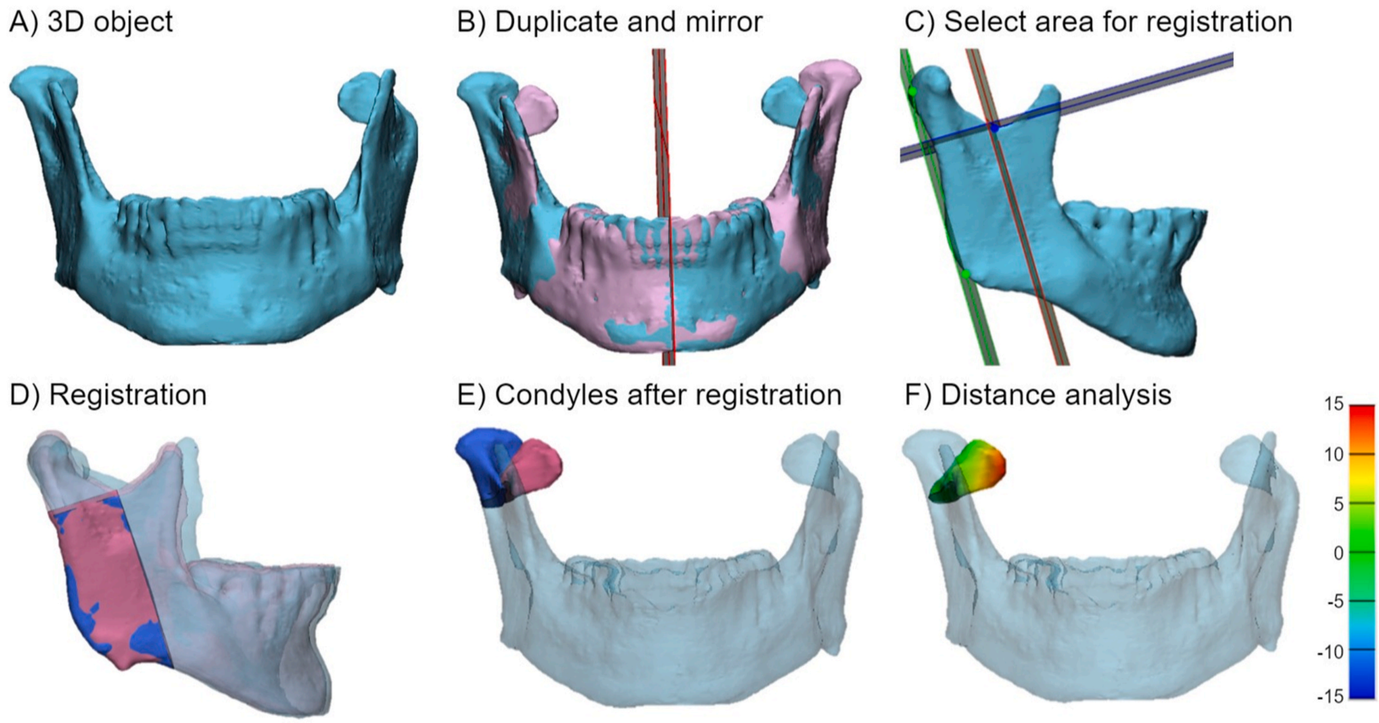

Fig. 2. Registration of affected mandibular condyle to contralateral healthy condyle. A. initial 3D object with the affected condyle at the left side; B. duplicated object (pink) of initial object (blue), mirrored over midplane; C. posterior ramus plane (green), sigmoid notch plane (blue), and parallel ramus plane (red) defining the selected area for registration; D. registration of mirrored and initial objects based on selected areas; E. position of affected condyle related to the healthy condyle after registration; F. colormap presenting distance (mm) between condyles.

taking the square root. The RMS provided information about the extent of differences between the 3D positions of both condyles.

Analysis of the 3D position of the affected condyle in comparison to the healthy condyle was elaborated in 3DMedX® (Version 1.2.24.0, 3D Lab RadboudUMC, Nijmegen, Netherlands). The positions of both condyles after the refined registration were set as the initial positions. Next, the affected and healthy condyles were aligned using the ICP algorithm based on the condylar heads. The performed transformation was saved, and the translations and rotations of the affected condyle were extracted. The translations presented the displacement of the affected condyle compared to the healthy condyle in the medial-lateral, anterior-posterior, and inferior-superior directions. The rotations demonstrated the pitch, roll, and yaw of the affected condyle with the condyle object origin as the center of rotation. Pitch, roll, and yaw were the rotations around the medial-lateral, anterior-posterior, and inferior-superior axis, respectively. Translations and rotations were presented in absolute values. Moreover, the total 3D Euclidean distance was calculated by taking the square root of the sum of the squared translations in each of the three directions. In addition, the sum of the rotations was calculated as an estimate of the total rotation.

2.4.4. Reliability

The reliability of the data processing was evaluated for the segmentation and registration steps.

Good to excellent inter- and intraobserver reliability has already been reported for semi-automatic segmentation of mandibular condyles on CBCT scans (Méndez-Manjón et al., 2019; Nicolielo et al., 2017; Xi et al., 2014). To verify the reliability of the segmentation of condyles treated for unilateral fracture, segmentation was performed twice by the same observer with an interval of 1 month and once by another observer for a sample of the included patients (three randomly selected patients from each group). The Dice similarity coefficient (DSC) was determined between segmentations of the affected condyle, healthy condyle, and mandible without dental area. The DSC statistically measures the similarity based on the spatial overlap (Zou et al., 2004). The DSC was calculated by dividing two times the volume of the overlap between two segmentations by the total volume of these segmentations. The DSC could have values between 0 and 1, with 0 indicating no overlap and 1 presenting complete overlap between objects. Good overlap occurs when DSC $>$0.70 (Zou et al., 2004) The DSC for interobserver segmentations was $>$0.92 for the affected condyle, $>$0.94 for the unaffected condyle, and $>$0.96 for the mandible without dental area for all six patients. The DSC for intraobserver segmentations was $>$0.95, $>$0.94, and $>$0.97 for the affected condyle, unaffected condyle, and mandible without dental area, respectively. These good DSC values indicate that the method of segmentation was reliable.

To assess the inter- and intraobserver reliability of the semi-automatic registration, the registration was performed twice by the same observer with an interval of 1 month and once by another observer with the same segmented 3D objects for all included patients. Intraclass correlation coefficients (ICCs) were calculated between the condylar volumes, volume differences, and RMS of the distances. A two-way random model with an absolute agreement was applied. ICC(2,2) and ICC(2,1) were applied for inter- and intraobserver reliability respectively. ICCs were interpreted as poor ($<$0.50), moderate (0.50–0.75), good (0.76–0.90), and excellent ($>$0.90) reliability (Koo and Li, 2016). The inter- and intraobserver registrations resulted in ICCs $>$0.99 with P values of 0.000 for condylar volume, volume differences, and RMS of the distances, presenting excellent reliability of the registration method.

2.5. Mandibular functioning and pain

Mandibular functioning and pain were evaluated during the assessment 6 months after the start of treatment. Functioning was objectively assessed by the maximum mouth opening and masticatory performance. In addition, the masticatory ability and pain were evaluated as PROs. These mandibular functioning and pain scores were associated with the 3D position of the affected condyle regardless of the performed treatment modality.

2.5.1. Objective functional outcomes

The maximum mouth opening was measured by the maximum interincisal opening (MIO). The MIO was measured intraorally as the distance between the central incisors of the maxilla and mandible in closed and active maximal open positions. Excellent reliability (ICC = 0.88–0.98) was reported for the MIO (Rauch and Schierz, 2018).

The masticatory performance was evaluated by the Utrecht Mixing Ability Test (MAT). A comprehensive description of the MAT was previously published (de Groot et al., 2018; Speksnijder et al., 2009; van der Bilt et al., 2012). The MAT assesses the patient's ability to mix two wax layers of the colors red and blue. The outcome of the MAT is the Mixing Ability Index (MAI), which evaluates the ability to mix both colors in 15 chewing strokes. The MAI is obtained by measuring the intensity distribution of the red and blue colors in digital photographs of both sides of the wax after flattening. The MAI ranges from 5 to 30, with 5 presenting a fully mixed wax tablet and 30 an unmixed tablet. The better the mixing, the better the masticatory performance. Excellent test–retest reliability (ICC = 0.91) was reported for the MAT in condylar trauma patients (Weinberg et al., 2019).

2.5.2. Patient-reported outcomes

The masticatory ability was assessed by the Mandibular Function Impairment Questionnaire (MFIQ), which is a reliable instrument for measuring a patient's perception of mandibular functioning (Kropmans et al., 1999; Stegenga et al., 1993; Weinberg et al., 2019). This questionnaire consists of 17 items. Each item is scored using a five-point Likert scale on which patient indicate their experienced level of difficulty while performing mandibular movements or tasks. The total outcome ranged from 0 to 68, with 0 presenting no mandibular function impairment and 68 a poor functional outcome.

The patient's experienced pain was scored by a visual analog scale (VAS_{pain}). This VAS_{pain} consists of a 100-mm horizontal line on which the patient chooses a position, with 0 mm indicating no pain and 100 the worst imaginable pain. The VAS_{pain} was reported to be reliable to assess acute pain (Hawker et al., 2011).

2.6. Morphology

The morphology of the affected condyle was classified according to the AOCMF classification based on all three CT/CBCT scans of each patient. This classification evaluated the fragmentation, sideward displacement, and angulation of the condylar fracture. Fragmentation was classified as none (0), minor (1), or major (2), depending on the number of fragments and structural integrity of the condylar process. Six months after the start of the treatment, the condylar fractures were ossified, meaning that there was no fragmentation. Sideward displacement was classified as none (0), partial (1), or full (2), independent of the direction of displacement. Angulation was classified as <5° (0), 5–45° (1), or >45° in any direction (Neff et al., 2014). The affected condyles were classified by two observers until consensus was achieved. In addition, classifications were compared between consecutive scans and categorized as improved, unchanged, or deteriorated.

2.7. Statistical analysis

Descriptive statistics were used to describe patient characteristics. Normal distributed continuous data were presented as means and standard deviations, ordinal and non-normal distributed continuous data as medians and interquartile ranges (IQRs), and nominal as frequencies. Normal distribution was assessed visually and evaluated with the Shapiro–Wilk test and the z values of skewness and kurtosis. To determine significant differences between the open and closed treatment groups, the independent *t*-test was applied for normally distributed continuous data, the Mann–Whitney *U* test for ordinal and non-normally distributed continuous data, and the χ^2 test or Fisher exact test for nominal data. The Pearson (r; normally distributed continuous data) or Spearman (r_s; non-normally distributed continuous data) correlation coefficient was obtained to correlate the 3D position of the affected condyle with mandibular functioning and pain scores for the patients of both groups together. Absolute values of correlations were interpreted as weak (<0.35), moderate (0.35–0.67), high (0.68–0.89), and very high (≥0.90) (Taylor, 1990). *P* values < 0.05 were considered statistically significant. All statistical analyses were performed using SPSS software (version 27, IBM Corp., Armonk, NY, USA).

3. Results

Of the 33 participating patients included in the original controlled clinical trial, 12 were excluded from this study. These patients were excluded because of having an additional fracture in the area of CBCT registration (n = 2), absence of the follow-up scan (n = 6), incomplete capture of condyles at the follow-up scan (n = 3), or major movement artifact at the follow-up scan (n = 1). For this study, 11 patients were included in the open treatment group and 10 in the closed treatment group. There were no significant differences between the open and closed treatment groups in regard to age, sex, fractured side, fractured region, other mandibular fractures, occluding units, and mandibular functioning and pain scores, as depicted in Table 1. No physiotherapy was applied in both groups during the 6 months follow-up of this study.

4. 3D position

The (absolute) volume differences, RMS of the distances, translations in anterior-posterior and inferior-superior directions, total 3D distance,

Table 1
Characteristics of the patients receiving open or closed treatment.

Characteristic	Open treatment group (n = 11)	Closed treatment group (n = 10)	P-value
Age, y	51 (25–54)	29 (25–32)	.204[b]
Gender			.183[a]
Male	5	8	
Female	6	2	
Fractured side			.361[a]
Left	6	8	
Right	5	2	
Fractured region			.670[a]
Neck	4	5	
Base	7	5	
Other mandibular fractures			.601[a]
No	6	4	
Paramedian contralateral	1	4	
Corpus contralateral	1	1	
Angulus contralateral	2	1	
Multiple regions contralateral	1	0	
Trauma to treatment interval, d	1 (1–3)	2 (1–2)	.798[b]
OU	11 (10–11)	11 (10–12)	
Denture			
Yes	0	0	
No	11	10	
Treatment to follow-up scan interval, m	5.9 (5.7–6.4)	6.2 (5.5–6.7)	.673[b]
MAI at follow-up	17.4 (16.4–19.4)	16.9 (16.1–18.4)	.217[b]
MIO at follow-up, mm	46.0 (35.0–52.0)	44.0 (38.3–53.6)	.944[b]
MFIQ at follow-up	13.0 (0.0–18.0)	5.0 (0.5–8.5)	.156[b]
VAS_{pain} at follow-up	1.0 (0.0–5.0)	0.0 (0.0–2.3)	.332[b]

Data are presented as median (interquartile range) or frequency.
[a]Fisher's exact test, [b]Mann-Whitney U testd: days; m: months; MAI: mixing ability index; MFIQ: mandibular function impairment questionnaire; MIO: maximum interincisal opening; mm: millimeter; OU: Occluding Units; VAS_{pain}: visual analog scale for pain; y: years.

and rotations did not significantly differ between the open and closed treatment groups at 6 months follow-up. Only the translation in the medial-lateral direction significantly differed between both treatment groups, presenting less translation after open treatment (Table 2).

4.1. 3D position versus mandibular functioning and pain

Weak to moderate correlations were found between the 3D position and mandibular functioning and pain for the patients in the open and closed treatment groups together (Table 3). The MIO demonstrated significant correlations with the RMS ($r_s = -0.569$), absolute volume difference ($r_s = -0.460$), translation in the anterior-posterior direction ($r_s = -0.441$), and total 3D distance demonstrated ($r_s = -0.574$). There were no significant correlations found between any of the parameters describing the 3D position and the MAI. The pitch rotation was significantly correlated with the MFIQ ($r_s = 0.499$). The volume difference presented a significant correlation with VAS_{pain} ($r_s = -0.503$).

4.2. Morphology

The AOCMF classification of the morphology of the affected condyles on the pre-treatment, post-treatment, and follow-up CT/CBCT scans revealed no significant differences between the open and closed treatment groups (Table 4). There was a significant difference in the comparison of the pre- and post-treatment classification between both treatment groups. The classification was for more patients improved within the open treatment group compared to the closed treatment group. There was no significant difference in the comparison of the post-treatment and follow-up classification.

5. Discussion

The choice of open or closed treatment for unilateral fractures of the mandibular condyle remains controversial. This study compared open and closed treatment by the final 3D position of the affected condyle. The translation in the medial-lateral direction was the only parameter presenting the 3D position that significantly differed between both treatment groups, demonstrating less translation of the affected condyle compared to the pursued anatomical position after open treatment. Associating the 3D position of the affected condyle with mandibular functioning and pain presented only weak to moderate correlations for the patients of open and closed treatment groups together. The AOCMF classification of the morphology of the affected condyles on the pre-treatment, post-treatment, and follow-up CT/CBCT scans revealed no significant differences between the open and closed treatment groups.

Table 2
Parameters presenting 3D position of the affected condyle of the patients receiving open or closed treatment at 6 months follow-up.

Parameter		Open treatment group (n = 11)	Closed treatment group (n = 10)	P-value
Volume difference, mm^3		64.4 (-185–234)	−220 (-294–124)	.260
Absolute volume difference, mm^3		185 (118–315)	241 (160–461)	.481
RMS of the distances		2.0 (1.4–3.5)	4.6 (2.5–6.4)	.078
Absolute translation, mm	Medial-lateral direction	0.3 (0.1–2.9)	4.1 (1.3–6.4)	.014*
	Anterior-posterior direction	1.3 (0.7–4.4)	3.9 (1.5–7.9)	.205
	Inferior-superior direction	1.3 (0.8–2.3)	2.1 (0.9–7.0)	.573
	Total 3D distance	2.5 (2.0–6.5)	8.0 (3.3–12.2)	.139
Absolute rotation, °	Pitch	8.0 (7.0–19.8)	9.1 (3.3–30.6)	.622
	Roll	7.0 (2.5–16.3)	12.0 (5.3–28.7)	.260
	Yaw	10.3 (2.0–17.5)	21.2 (2.3–34.3)	.159
	Sum of rotation	27.8 (21.1–47.7)	51.2 (36.2–71.1)	.057

Data are presented as median (interquartile range).
Statistical analyses are performed by the Mann-Whitney *U* test; *: $p < 0.05$.
3D: three dimensional; mm: millimeter; mm^3: cubic millimeter.

5.1. 3D position and morphology

Open treatment allows anatomical reduction. Therefore, minimal differences between the affected and healthy condyles were expected immediately after treatment. A prospective cohort study revealed mean displacements of the affected condyle compared to the healthy condyle of 0.8° and 1.9° for coronal and sagittal displacements, respectively, immediately after open treatment, indicating a good anatomical reduction (Ellis et al., 2000). Another study found that open reduction can produce a significant medial inclination to the condyle, which is related to clinical signs and symptoms (Mohamed et al., 2021). A randomized controlled trial (RCT) demonstrated a significant decrease in the angulation of the fractured condyle and shortening of the ascending ramus in the open treatment group from pre-operative to immediately post-operative, which was not so in the closed treatment group (Shiju et al., 2015). Similar results were found in our study, which demonstrated that 9 of the 11 patients had an improved morphology of the affected condyle immediately after open treatment. This was significantly different from the results for the patients after closed treatment. Most patients had an unchanged morphology immediately after the start of closed treatment.

However, postsurgical changes are known to occur. A prospective cohort study revealed that between 10% and 20% of the condyles had changes in positions of more than 10° between measurements immediately after surgery and 6 months follow-up (Ellis et al., 2000). That study presented mean displacements of the affected condyle compared to the healthy condyle that were 4.0° and 3.1° for coronal and sagittal displacement, respectively, at 6 months follow-up. Our study showed that the morphology of the affected condyle deteriorated for 2 of the 11 patients between the post-treatment and 6 months follow-up measurements after open treatment. One of these patients had a poor result of the open treatment, with the affected condyle placed in a non-anatomical position during surgery, and the morphology deteriorating during the post-operative course. None of the patients in the closed treatment group had a deteriorated morphology of the affected condyle between post-treatment and follow-up measurements. Nonetheless, the morphology of the affected condyle did not significantly differ between the open and closed treatment groups at 6 months follow-up.

The final position of the affected condyle was evaluated in more detail in earlier studies based on two-dimensional orthopantomograms and radiographs in Towne's view. A retrospective study demonstrated no statistically significant relationship between the method of treatment and coronal and sagittal displacement and loss of ramus height at 6 months follow-up (Villarreal et al., 2004). However, two other studies reported significantly less angulation of the affected condyle and shortening of the ascending ramus after open treatment compared to closed treatment at follow-up (Konstantinovic and Dimitrijevic, 1992; Shiju et al., 2015).

Our study showed that the final 3D position of the affected condyle was significantly more translated in medial-lateral direction compared to the healthy condyle after closed treatment than after open treatment. However, the other parameters presenting the 3D position did not significantly differ between groups (Table 2). For parameters presenting *P* values between 0.1 and 0.9, there is certainly no reason to suspect that these are different between open and closed treatment groups (Fisher, 1934). The RMS of the distances and sum of rotation had *P* values of 0.078 and 0.057, respectively. These values were larger than the designated threshold of significance for this study, but differences between open and closed treatment groups cannot be eliminated. The median values showed smaller RMS of the distances, (absolute) volume

Table 3
Spearman correlation coefficients between 3D position of the affected condyle and mandibular functioning and pain scores of the patients in open and closed treatment groups together at 6 months follow-up.

Spearman correlation coefficient			MAI	MIO	MFIQ	VAS_{pain}
Parameters 3D position	Volume difference		.085	.405	−.099	−.503*
	Absolute volume difference		−.123	−.460*	−.144	.257
	RMS of the distances		.011	−.569**	.069	−.010
	Absolute translation	Medial-lateral direction	−.054	−.351	−.111	−.012
		Anterior-posterior direction	−.130	−.441*	.285	.175
		Inferior-superior direction	.174	−.113	.191	−.133
		Total 3D distance	−.018	−.574**	.205	.089
	Absolute rotation	Pitch	.194	−.286	.499*	.050
		Roll	.049	−.363	.073	.154
		Yaw	.304	.035	−.284	−.159
		Sum of rotation	.212	−.398	.035	−.018

*: $P < 0.05$; **: $P < 0.01$.
MAI: mixing ability index; MFIQ: mandibular function impairment questionnaire; MIO: maximum interincisal opening; RMS: root mean square; VAS_{pain}: visual analog scale for pain.

Table 4
Morphology of mandibular condyle after fracture presented by the AOCMF fracture classification (Neff et al., 2014) for the patients receiving open or closed treatment based on (cone beam) computed tomography scans captured pre-treatment, post-treatment, and at 6 months follow-up.

AOCMF classification of affected condyl		Open treatment group (n = 11)	Closed treatment group (n = 10)[c]	*P*-value
Pre-treatment	Fragmentation	0 (0–1)	0 (0–0.25)	.254[b]
	None	6	8	
	Minor	3	1	
	Major	2	1	
	Sideward displacement	2 (1–2)	1.5 (0–2)	.193[b]
	None	1	4	
	Partial	2	1	
	Full	8	5	
	Angulation	1 (1–1)	1 (0–1.25)	.490[b]
	<5°	1	3	
	5–45°	8	5	
	>45°	2	2	
Post-treatment	Fragmentation	0 (0–0)	0 (0–0.50)	.392[b]
	None	10	7	
	Minor	1	1	
	Major	0	1	
	Sideward displacement	0 (0–1)	2 (0–2)	.097[b]
	None	8	4	
	Partial	2	0	
	Full	1	5	
	Angulation	0 (0–1)	1 (0–1.5)	.301[b]
	<5°	6	3	
	5–45°	4	4	
	>45°	1	2	
Follow-up	Fragmentation	0 (0–0)	0 (0–0)	1.000[b]
	None	11	10	
	Minor	0	0	
	Major	0	0	
	Sideward displacement	0 (0–0)	0 (0–2)	.118[b]
	None	10	6	
	Partial	0	1	
	Full	1	3	
	Angulation	1 (0–1)	1 (0–1.25)	.397[b]
	<5°	5	3	
	5–45°	5	5	
	>45°	1	2	
Post-treatment versus pre-treatment				.002[a]*
Improved		9	1	
Unchanged		1	7	
Deteriorated		1	1	
Follow-up versus post-treatment				.642[a]
Improved		3	2	
Unchanged		6	7	
Deteriorated		2	0	

Data are presented as median (interquartile range) for ordinal data with frequencies for each category, and as frequency for nominal data.
[a]Fisher's exact test, [b]Mann-Whitney *U* test; *: $P < 0.05$; [c]: n = 9 for post treatment classification for closed treatment group.

differences, translations, and rotations for treated condyles after open treatment compared to closed treatment. This suggests that the 3D position of the treated condyle might be more symmetric to the contralateral condyle after open treatment compared to closed treatment, implying a better anatomical result after treatment.

5.2. 3D position versus mandibular functioning and pain

The best association was found between the total 3D distance and MIO with $r_s = -0.574$, indicating that the larger the translation of the affected condyle in any direction, the smaller the mouth opening. The second best association was found between the RMS of the distances and MIO with $r_s = -0.569$, meaning the larger the distance (either positive or negative) between the healthy and mirrored and transformed affected condyles, the smaller the mouth opening. Other significant associations with the MIO were found for the translation in the anterior-posterior direction and the absolute volume difference, also presenting moderate negative correlations. Thus, a worse position of the affected condyle is moderately correlated with lower MIO.

None of the parameters presenting the 3D position of the affected condyle were significantly associated with the MAI, suggesting that the objective efficiency of the masticatory process is not affected by the 3D position of the affected condyle. The MAI of both treatment groups in our study equals the MAI of healthy subjects, presenting a good clinical outcome (Speksnijder et al., 2009). Mastication does not only depend on the condylar position, but also on muscles, ligaments, and occlusal units. Musculature, skeleton, and dentition adapt for a favorable outcome after condylar fracture. Earlier research demonstrated that restoring the condyle after fracture to its initial position does little to alter changes in chewing patterns (Ellis and Throckmorton, 2005). This supports our finding that the 3D position of the condyle is not significantly associated with the MAI.

The association between the patients' experience and the 3D position of the affected condyle was restricted. The MFIQ presented only a significant correlation with pitch rotation with $r_s = 0.499$ at 6 months follow-up. The larger the rotation of the condyle to anterior or posterior, the higher the MFIQ score, which means a poorer experience of mandibular functioning.

The experienced pain correlated significantly only with the volume difference between affected and healthy condyles with $r_s = -0.503$. This negative correlation shows that negative volume differences are associated with higher VAS_{pain} and positive volume differences with lower VAS_{pain}. Negative volume differences occurred when the volume of the affected condyle was less than the volume of the healthy condyle, for instance, due to relapse. Thus, a poorer position of the condyle is associated with more pain at 6 months follow-up. Positive volume differences could have occurred due to remodeling of the treated side. This suggests that a remodeled bone does not necessarily lead to pain.

No other studies were identified that associated the 3D position of condyles with mandibular functioning or pain in patients after a unilateral fracture. Earlier studies associated the position of the condyle in the fossa with other functional outcomes than evaluated in our study for patients with non-traumatic oral–maxillofacial pain or healthy subjects (Kiseri et al., 2018; Sener, 2011).

5.3. Strengths and limitations

To the best of our knowledge, this was the first study to compared the position of the affected condyle between patients after open and closed treatment based on 3D analysis, and the first study to associate this 3D position with mandibular functioning and pain. The data processing of CBCT scans was extensively documented, which allows reproduction for future research. The data processing was automated as much as possible to eliminate operator errors and to facilitate a less time-consuming workflow. The applied methods of segmentation and registration were proved to be reliable.

The affected condyle was compared to the healthy contralateral condyle. Anatomical variations in position and morphology between healthy contralateral condyles were not considered in the analysis. The anatomical variation depends on the growth pattern, as evaluated in a cross-sectional study (Ganugapanta et al., 2017). That study found that condyles in non-traumatic patients with normal occlusion showed no significant asymmetry for the diameter of the condyle and the position of the condyle in the fossa. Significant differences were reported for the position of both condyles related to the mid-sagittal plane. Our study registered the condyles at the ascending ramus, so the comparison of the condyles was not performed related to the mid-sagittal plane. Therefore, it is expected that the anatomical variation in position and morphology of condyles would not have significantly affected the results.

The RMS of the distances between affected and healthy condyles was retrieved from closest point calculations. This closest point did not automatically correspond to the same anatomical location, especially in large deviations between the object surfaces. Correspondent point calculations use shape analysis to map the distance between correspondent anatomical points (Verhelst et al., 2020). The use of correspondent point calculations for comparing affected and healthy condyles could be investigated. It may lead to more accurate results, but in-depth knowledge is required to make use of this technique, which makes it difficult for the wider medical community.

This study was performed in two different hospitals with different treatment protocols for unilateral condyle fractures, which limits the risk of inclusion bias. Included patients were part of a controlled clinical trial. This remains less strong than an RCT; however, trauma patients are less likely to participate in a randomized study, mainly because of personal preference for one form of treatment and the dislike of the idea of randomization (Abraham et al., 2006).

5.4. Recommendations

This study provides insight into the final position of affected condyles after open or closed treatment; however, this should be interpreted with caution because of the small sample size. More research is necessary to underline the differences or similarities in condylar anatomy between open and closed treatment.

None of the 3D position parameters that significantly correlated with mandibular functioning or pain scores significantly differed between the open and closed treatment groups. The 3D position parameters that were significantly associated with mandibular functioning seem to be of no significant influence on the choice of treatment.

Therefore, it may be preferable to avoid surgery and concomitant complications (Rozeboom et al., 2018a). Besides, closed treatment avoids operating room time, more expensive equipment, a longer time, hospitalization, and sickness leave cost (Rozeboom et al., 2018b). However, closed treatment requires more patient commitment, since more visits to the outpatient clinic may be necessary. Open treatment is preferable in specific patients, but future research is necessary to demonstrate which treatment is indicated for which patients (Valiati et al., 2008).

6. Conclusion

In conclusion, open treatment of unilateral condylar fractures resulted in a better fracture reduction than closed treatment, considering the significantly lower translation in the medial-lateral direction of the affected condyle compared to the pursued anatomical position at 6 months follow-up. The final position of the affected condyle was not associated with masticatory performance; however, a worse position was associated with a smaller mouth opening. A worse pitch rotation of the affected condyle was associated with a worse patient-reported masticatory ability. In addition, patients who had a volume reduction of the affected condyle reported more pain.

Declaration of interest

The authors report no competing interests in regard to this work.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abraham, N.S., Young, J.M., Solomon, M.J., 2006. A systematic review of reasons for nonentry of eligible patients into surgical randomized controlled trials. Surgery 139, 469–483. https://doi.org/10.1016/j.surg.2005.08.014.

Al-Moraissi, E.A., Ellis III, E., 2015. Surgical treatment of adult mandibular condylar fractures provides better outcomes than closed treatment: a systematic review and meta-analysis. J. Oral Maxillofac. Surg. 73, 482–493. https://doi.org/10.1016/j.joms.2014.09.027.

Cabral, L.C., Alves, G.M., Furtado, L.M., Fernandes Neto, A.J., Simamoto Júnior, P.C., 2020. Changes in mandibular and articular dynamics associated with surgical versus nonsurgical treatment of mandibular condylar fractures: a systematic review with meta-analysis. Oral Surg. Oral Med. Oral Pathol. Oral Radiol. 129, 311–321. https://doi.org/10.1016/j.oooo.2019.10.010.

Cavalcanti, S.C.S.X.B., Taufer, B., Rodrigues, A.F., Luz, J.G.C., 2021. Endoscopic surgery versus open reduction treatment of mandibular condyle fractures: a meta-analysis. J. Cranio-Maxillo-Fac. Surg. 49, 749–757.

Danda, A.K., Muthusekhar, M.R., Narayanan, V., Baig, M.F., Siddareddi, A., 2010. Open versus closed treatment of unilateral subcondylar and condylar neck fractures: a prospective, randomized clinical study. J. Oral Maxillofac. Surg. 68, 1238–1241. https://doi.org/10.1016/j.joms.2009.09.042.

de Groot, R.J., Wetzels, J., Merkx, M.A.W., Rosenberg, A.J.W.P., Haan, A.F.J., Bilt, A., Abbink, J.H., Speksnijder, C.M., 2018. Masticatory function and related factors after oral oncological treatment: a 5-year prospective study. Head Neck 41, 216–224. https://doi.org/10.1002/hed.25445.

Devireddy, S.K., Kishore Kumar, R.V., Gali, R., Kanubaddy, S.R., Dasari, M.R., Siddhartha, M., 2014. Three-dimensional assessment of unilateral subcondylar fracture using computed tomography after open reduction. Indian J. Plast. Surg. 47, 203–209. https://doi.org/10.4103/0970-0358.138945.

Du, C., Xu, B., Zhu, Y., Zhu, M., 2021. Radiographic evaluation in three dimensions of condylar fractures with closed treatment in children and adolescents. J. Cranio-Maxillo-Fac. Surg. 49, 830–836.

Ellis, E., Throckmorton, G.S., 2005. Treatment of mandibular condylar process fractures: biological considerations. J. Oral Maxillofac. Surg. 63, 115–134. https://doi.org/10.1016/j.joms.2004.02.019.

Ellis, E., Throckmorton, G.S., Palmieri, C., 2000. Open treatment of condylar process fractures: assessment of adequacy of repositioning and maintenance of stability. J. Oral Maxillofac. Surg. 58, 27–34. https://doi.org/10.1016/S0278-2391(00)80010-5.

Fisher, R.A., 1934. Tests of goodness of fit, independence and homogeneity; with table of chi-square. In: Statistical Methods for Research Workers. Oliver and Boyd, London, p. 82.

Fonseca, R., Walker, R., Bettx, N., Barber, H., 1991. Treatment of mandibular condylar fractures. In: Oral and Maxillofacial Trauma. WB Saunders, Philadelphia, pp. 527–567.

Ganugapanta, V.R., Ponnada, S.R., Gaddam, K.P.R., Perumalla, K., Khan, I., Mohammed, N.A., 2017. Computed tomographic evaluation of condylar symmetry and condyle-fossa relationship of the temporomandibular joint in subjects with normal occlusion and malocclusion: a comparative study. J. Clin. Diagn. Res. 11 https://doi.org/10.7860/JCDR/2017/21678.9328. ZC29–ZC33.

Han, X., Shao, X., Lin, X., Gui, W., Zhang, M., Liang, L., 2020. Open surgery versus closed treatment of unilateral mandibular condyle fractures. J. Craniofac. Surg. 31, 484–487. https://doi.org/10.1097/SCS.0000000000006080.

Handschel, J., Rüggeberg, T., Depprich, R., Schwarz, F., Meyer, U., Kübler, N.R., Naujoks, C., 2012. Comparison of various approaches for the treatment of fractures of the mandibular condylar process. J. Cranio-Maxillo-Fac. Surg. 40, e397–e401. https://doi.org/10.1016/j.jcms.2012.02.012.

Hawker, G.A., Mian, S., Kendzerska, T., French, M., 2011. Measures of adult pain: visual analog scale for pain (VAS pain), numeric rating scale for pain (NRS pain), McGill pain questionnaire (MPQ), short-form McGill pain questionnaire (SF-MPQ), chronic pain grade scale (CPGS), short form-36 bodily pain scale (SF). Arthritis Care Res. 63, 240–252. https://doi.org/10.1002/acr.20543.

Kiseri, B., Dayan, S.Ç., Yıldız, M., Sülün, T., 2018. The correlation between direction and amount of retrusive movement and condyle position and joint space. Cranio - J. Craniomandib. Pract. 36, 250–256. https://doi.org/10.1080/08869634.2017.1333219.

Kommers, S.C., van den Bergh, B., Forouzanfar, T., 2013. Quality of life after open versus closed treatment for mandibular condyle fractures: a review of literature. J. Cranio-Maxillo-Fac. Surg. 41, e221–e225. https://doi.org/10.1016/j.jcms.2013.01.022.

Konstantinovic, V.S., Dimitrijevic, B., 1992. Surgical versus conservative treatment of unilateral condylar process features: clinical and radiographic evaluation of 80 patients. Group 50, 349–352. https://doi.org/10.1016/0278-2391(92)90395-G.

Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J. Chiropr. Med. 15, 155–163. https://doi.org/10.1016/j.jcm.2016.02.012.

Kropmans, T.J.B., Dijkstra, P.U., Van Veen, A., Stegenga, B., De Bont, L.G.M., 1999. The smallest detectable difference of mandibular function impairment in patients with a painfully restricted temporomandibular joint. J. Dent. Res. 78, 1445–1449.

Li, J., Yang, H., Han, L., 2019. Open versus closed treatment for unilateral mandibular extra-capsular condylar fractures: a meta-analysis. J. Cranio-Maxillo-Fac. Surg. 47, 1110–1119. https://doi.org/10.1016/j.jcms.2019.03.021.

McLeod, N.M., Keenan, M., 2021. Towards a consensus for classification of mandibular condyle fractures. J. Cranio-Maxillo-Fac. Surg. 49, 251–255.

Méndez-Manjón, I., Orion Luiz, H.J., Raquel, G.M., Rogério, B.D.O., Adaia, V.O., Federico, H.A., 2019. Semi-automated three-dimensional condylar reconstruction. J. Craniofac. Surg. 30, 2555–2559. https://doi.org/10.1097/SCS.0000000000005781.

Mohamed, A.A.S., Abotaleb, B., Ahmed Abdulqader, A., Hongliang, D., Sakran, K.A., He, D., 2021. Three-dimensional assessment of accuracy for open reduction and internal fixation of the subcondylar fracture and its implications on the TMJ function. J. Cranio-Maxillo-Fac. Surg. 49, 1035–1043. https://doi.org/10.1016/j.jcms.2021.06.009.

Montazem, A.H., Anastassov, G., 2009. Management of condylar fractures. Atlas oral maxillofac. Surg. Clin. 17, 55–69. https://doi.org/10.1016/j.cxom.2008.11.002.

Neff, A., Cornelius, C.-P., Rasse, M., Torre, D.D., Audigé, L., 2014. The comprehensive AOCMF classification system: condylar process fractures - level 3 tutorial. Craniomaxillofacial Trauma Reconstr. 7, S044–S058. https://doi.org/10.1055/s-0034-1389559.

Nicolielo, L.F.P., Van Dessel, J., Shaheen, E., Letelier, C., Codari, M., Politis, C., Lambrichts, I., Jacobs, R., 2017. Validation of a novel imaging approach using multi-slice CT and cone-beam CT to follow-up on condylar remodeling after bimaxillary surgery. Int. J. Oral Sci. 9, 139–144. https://doi.org/10.1038/ijos.2017.22.

Rauch, A., Schierz, O., 2018. Reliability of mandibular movement assessments depending on TMD. Cranio - J. Craniomandib. Pract. 36, 156–160. https://doi.org/10.1080/08869634.2017.1325986.

Rozeboom, A.V.J., Speksnijder, C.M., Dubois, L., Lobbezoo, F., Koutris, M., de Lange, J., 2018. Is masticatory performance affected after a unilateral condylar fracture? A cross-sectional study. J. Oral Rehabil. 45, 777–782. https://doi.org/10.1111/joor.12688.

Rozeboom, A.V.J., Dubois, L., Bos, R.R.M., Spijker, R., de Lange, J., 2018a. Open treatment of condylar fractures via extraoral approaches: a review of complications. J. Cranio-Maxillofacial Surg. 46, 1232–1240. https://doi.org/10.1016/j.jcms.2018.04.020.

Rozeboom, A.V.J., Klumpert, L.T., Koutris, M., Dubois, L., Speksnijder, C.M., Lobbezoo, F., de Lange, J., 2018b. Clinical outcomes in the treatment of unilateral condylar fractures: a cross-sectional study. Int. J. Oral Maxillofac. Surg. 47, 1132–1137. https://doi.org/10.1016/j.ijom.2018.05.021.

Sener, S., 2011. Correlation between the condyle position and intra-extraarticular clinical findings of temporomandibular dysfunction. Eur. J. Dermatol. 5, 354–360. https://doi.org/10.1055/s-0039-1698905.

Shiju, M., Rastogi, S., Gupta, P., Kukreja, S., Thomas, R., Bhugra, A.K., Parvatha Reddy, M., Choudhury, R., 2015. Fractures of the mandibular condyle—open versus closed—a treatment dilemma. J. Cranio-Maxillofacial Surg. 43, 448–451.

Singh, P., Mohanty, S., Chaudhary, Z., Sharma, P., Kumar, J., Verma, A., 2022. Does mandibular condylar morphology after fracture healing predict functional outcomes in patients treated with closed reduction? J. Oral Maxillofac. Surg. 80, 691–699. https://doi.org/10.1016/j.joms.2021.11.008.

Speksnijder, C.M., Abbink, J.H., Van Der Glas, H.W., Janssen, N.G., Van Der Bilt, A., 2009. Mixing ability test compared with a comminution test in persons with normal and compromised masticatory performance. Eur. J. Oral Sci. 117, 580–586. https://doi.org/10.1111/j.1600-0722.2009.00675.x.

Stegenga, B., de Bont, L.G., de Leeuw, R., Boering, G., 1993. Assessment of mandibular function impairment associated with temporomandibular joint osteoarthrosis and internal derangement. J. Orofac. Pain 7, 183–195.

Taylor, R., 1990. Interpretation of the correlation coefficient. A B. J. Diagnostic Med. Sonogr. 6, 35–39. https://doi.org/10.1177/875647939000600106.

Valiati, R., Ibrahim, D., Abreu, M.E.R., Heitz, C., De Oliveira, R.B., Pagnoncelli, R.M., Silva, D.N., 2008. The treatment of condylar fractures: to open or not to open? A critical review of this controversy. Int. J. Med. Sci. 5, 313–318. https://doi.org/10.7150/ijms.5.313.

van der Bilt, A., Speksnijder, C.M., de Liz Pocztaruk, R., Abbink, J.H., 2012. Digital image processing versus visual assessment of chewed two-colour wax in mixing ability tests. J. Oral Rehabil. 39, 11–17. https://doi.org/10.1111/j.1365-2842.2011.02229.x.

Verhelst, P.J., Verstraete, L., Shaheen, E., Shujaat, S., Darche, V., Jacobs, R., Swennen, G., Politis, C., 2020. Three-dimensional cone beam computed tomography analysis protocols for condylar remodelling following orthognathic surgery: a systematic review. Int. J. Oral Maxillofac. Surg. 49, 207–217. https://doi.org/10.1016/j.ijom.2019.05.009.

Villarreal, P.M., Monje, F., Junquera, L.M., Mateo, J., Morillo, A.J., González, C., 2004. Mandibular condyle fractures: determinants of treatment and outcome. J. Oral Maxillofac. Surg. 62, 155–163. https://doi.org/10.1016/j.joms.2003.08.010.

Weinberg, F.M., Vermaire, J.A., Forouzanfar, T., Rosenberg, A.J.W.P., Speksnijder, C.M., 2019. Reproducibility and construct validity of the utrecht mixing ability test to obtain masticatory performance outcome in patients with condylar mandibular fractures. J. Oral Rehabil. 1–7. https://doi.org/10.1111/joor.12917, 00.

World Medical, Association., 2013. World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. JAMA 27, 2191–2194. https://doi.org/10.1001/jama.2013.281053.
Xi, T., Schreurs, R., Heerink, W.J., Bergé, S.J., Maal, T.J.J., 2014. A novel region-growing based semi-automatic segmentation protocol for three-dimensional condylar reconstruction using cone beam computed tomography (CBCT). PLoS One 9, 9–14. https://doi.org/10.1371/journal.pone.0111126.
Zou, K.H., Warfield, S.K., Bharatha, A., Tempany, C.M.C., Kaus, M.R., Haker III, S.J., W M, W., Jolesz, F.A., 2004. Statistical validation of image segmentation quality based on spatial overlap index. Acad. Radiol. 11, 178–189. https://doi.org/10.1016/S1076-6332(03)00671-8.