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# Extraction of 3D trajectories of mandibular condyles from 2D real-time MRI

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## Abstract

*Object:* Computing the trajectories of mandibular condyles directly from MRI could provide a comprehensive examination, providing both anatomical and kinematic details. This study aimed to investigate the feasibility of extracting 3D condylar trajectories from 2D real-time MRI.

*Materials and Methods:* Twenty healthy subjects underwent real-time MRI while performing jaw opening and closing movements. One axial and two sagittal slices were segmented using a U-Net-based algorithm. After motion compensation, the centers of mass of the resulting masks were projected onto the coordinate system based on anatomical markers and temporally adjusted. The quality of the computed trajectories was evaluated using metrics designed to estimate movement reproducibility, head motion, and slice placement symmetry.

*Results:* The segmentation of the axial slices demonstrated good-to-excellent quality; however, the segmentation of the sagittal slices required some fine-tuning. On average, the intercuspal position shifted by 0.6 mm after an opening-closing cycle. The difference in the superior-inferior coordinate of the condyles in the intercuspal position was 1.5 mm on average. Some subjects demonstrated a significant discrepancy between the axial and the sagittal trajectories.

*Discussion:* Real-time MRI enables the extraction of condylar trajectories for evaluating some clinically relevant parameters. However, attention is required during patient installation and image acquisition.

## Keywords

Temporomandibular joints, real-time MRI, trajectories, condylar kinematics

## Acknowledgment.

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# INTRODUCTION

Temporomandibular joint disorder (TMD) is a common condition that needs careful diagnosis and treatment planning. Its typical symptoms comprise jaw pain or dysfunction, earache, headache, and facial pain. Understanding the kinematics of mandibular condyles is crucial for TMD management [1,2].

Computerized mechanical axiography [3] has long been the traditional method for tracking the 3D motion of the jaw [4]. However, modern advancements have led to the development of jaw-tracking systems employing ultrasound [5], and infrared or optical cameras [6–11]. Numerous jaw-tracking devices are commercialized [12] and demonstrate excellent theoretical measurement precision [13] and a good correlation with direct measurements [14]. However, they share common drawbacks. Firstly, many require the cutaneous or intra-oral attachment of markers or sensors, potentially causing discomfort and hygiene issues. Although some approaches utilize artificial intelligence algorithms to mitigate this issue [15], this work is still in progress. Secondly, most rely on extra-oral tracking points, resulting in indirect measurements. Finally, in some cases, they still require supplementation with MRI or CT scans for detailed anatomical information.

CT imaging stands as the gold standard for imaging bone tissues, demonstrating its clinical validity [16]. Cone beam CT scanning can be used for tracking 3D condylar trajectories [14,17]; however, the presence of ionizing radiation becomes an ethical issue when a long recording is required. Additionally, hard tissues are typically injured later than soft tissues like the intra-articular disc or capsule [18]. Therefore MRI, which is the gold standard technique for soft tissue imaging [19,20], is frequently prescribed by clinicians. Despite the MRI's long acquisition time complicating dynamic imaging, multiple acquisition and reconstruction strategies allow fast good-quality recordings [21]. Several studies have shown the applicability of the real-time MRI to temporomandibular joint imaging [22–24]. Complementing static high-resolution anatomical MRI with condylar trajectories extracted directly from dynamic MRI would offer a comprehensive, non-invasive, and ionizing radiation-free examination.

The goal of this work was to propose and evaluate the reliability of an automatic algorithm allowing extraction of 3D trajectories of mandibular condyles from 2D real-time MRI. Firstly, we assess the precision of automatic segmentation predictions. Then, we describe and demonstrate the trajectory extraction method and the refinements applied to

minimize errors. Finally, we introduce a set of quality metrics aimed at evaluating the validity of the extracted trajectories.

## **MATERIALS AND METHODS**

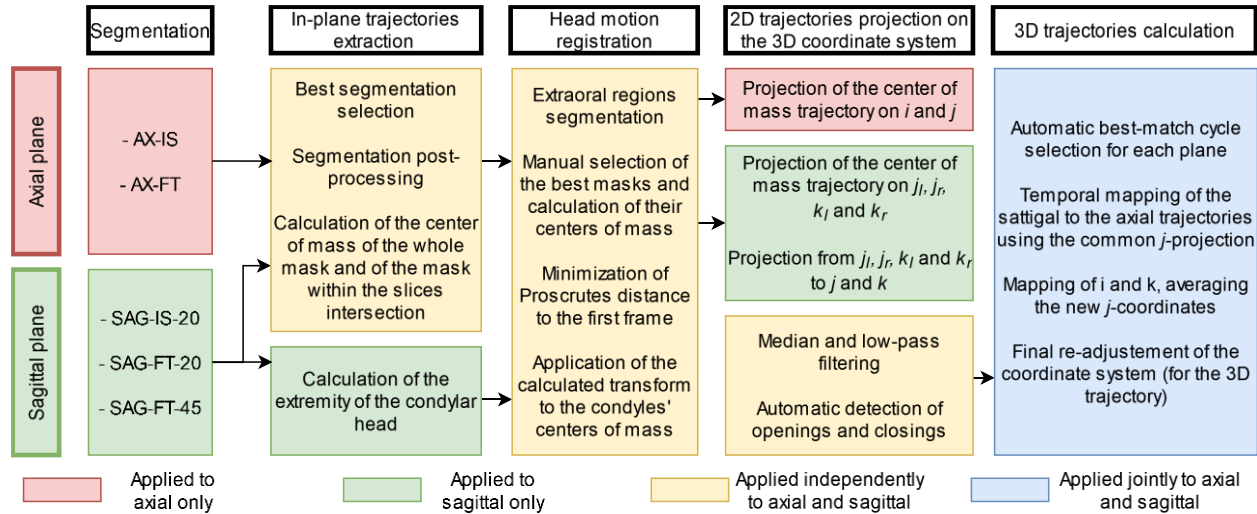
### **Participants and data acquisition**

20 healthy volunteers with no known temporomandibular pathologies were recruited. All participants provided written informed consent. The data was acquired under two approved ethical protocols: “METHODO” (ClinicalTrials.gov Identifier: NCT02887053, approval: CPP EST-III, 08.10.01) and its successor “EDEN” (ClinicalTrials.gov Identifier: NCT05218460, approval: CPP SUD-EST IV, 26.07.21). This study was performed in line with the principles of the Declaration of Helsinki.

The images were acquired on a 3T Siemens Prisma. A static anatomical 3D SPACE sequence (TE/TR=11/700 ms, FoV=260 mm, 256x256, 1 mm slice thickness) was employed at the beginning of the protocol. The dynamic images were acquired with a radial undersampled 2D FLASH sequence [25]. The dynamic MRI was performed in 3 different planes. Two simultaneously imaged oblique sagittal planes passed through the condyles and the canine teeth on the axial localizer and were parallel to the mandibular ramus on the coronal localizer (TE/TR=1.35/2.5 ms, FoV=100 mm, 168x168, 6 mm slice thickness, image acquisition time 52.5 ms). One oblique axial slice traversed both condyles and was parallel to the horizontal Frankfurt plane (TE/TR=1.47/2.34, FoV=192 mm, 136x136, 8 mm slice thickness, image acquisition time 21.1 ms). The selected real-time sequences were acquired at the end of the imaging protocol, with a 10-15 minute interval between them. The axial sequence was performed first, followed by the sagittal sequence. For the two first subjects of the set, there was no simultaneous acquisition of both condyles in sagittal planes. The volunteers were asked to slowly open and close the jaw with a periodicity of approximately 6 seconds; however, the actual speed of movement varied among volunteers.

### **Trajectories extraction**

The trajectories were calculated as schematically described in Fig. 1.

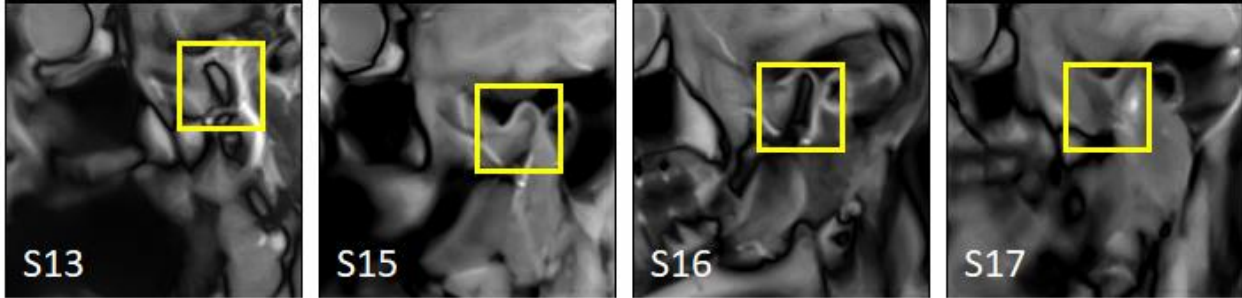


**Fig. 1.** Illustration depicting the process for computing condylar trajectories.

## Segmentation

To ensure optimal diversity within the development set, we performed a k-means clustering analysis, similarly to as described in [23]. The selected 20 images were annotated by an expert (JL, a dental surgeon with 10 years of experience). Therefore, a segmented set of  $20 \times 20 = 400$  images for each slice orientation and each condyle side was available. The segmentation routine included cropping to a manually selected region of interest (ROI), data augmentation (translations and rotations), and training using a U-Net convolutional neural network [26]. The implementation and training details are described in [23].

To evaluate the impact of this variability on the segmentation results, two different segmentation strategies were explored for the axial plane. The first one (AX-IS, IS for inter-subject) utilized the first 70% of available subjects (14 subjects) as the training set, 10% (2 subjects) as the validation set, and the remaining 20% (4 subjects) as the test set. For the second approach (AX-FT), the model from the IS training was fine-tuned (FT) for each subject. For that, 70% of the images available for each subject (14 images) were used as the training set, 10% (2 images) as the validation set, and 20% (4 images per subject) as the test set. An ROI of 30% of the FOV (58 mm) was selected.



**Fig. 2.** Illustration of the condyle's appearance for different subjects with different placements of the sagittal plane.

The condyles segmentation in the sagittal plane was a challenging task due to the high sensibility of their contrast on the plane position (see Fig. 2). A ROI of 45% of the FOV (45 mm) was sufficient to cover the condyles' motion. However, the preliminary numerical experiments had shown the impossibility of adequately training the IS model using this ROI size. Therefore, three different strategies were tested for the segmentation of the condyles in the sagittal planes. The first one (SAG-IS-20) performed the segmentation within a small ROI of 20% of the initial FOV (20 mm). This ROI size was, however, too small to include the condyles during their motion. Thus, the segmentation was combined with basic center mass tracking. For each frame, a new ROI was centered on the mass center of the previous segmentation mask. The second approach (SAG-FT-20) expanded the first one by fine-tuning the model for each subject. The third one (SAG-FT-45) exploited the IS-trained model to retrain it using the FOV of 45 mm. For the last two strategies, the train-validation-test distribution was the same as before (70%-10%-20%).

The segmentation results were evaluated using several quantitative metrics: Dice similarity coefficient, precision, recall, and distance between the center of mass (DCM) of the predicted and the ground truth masks. The results are provided in the format  $\text{mean} \pm \text{standard deviation}$ . Additionally, an expert performed a blind qualitative evaluation of the whole series' segmentation (JL). For this, video sequences with the segmented condyles were generated in a randomized order. The following scores were used: 0 – Completely failed segmentation, 1 - Bad segmentation quality, serious errors that will substantially change the trajectory, 2 - Medium segmentation quality, overall correct, but imprecise, 3 - Good segmentation quality, there are no visible errors. Additionally, the expert had to select the best segmentation video (only one choice was allowed). The segmentation quality was considered acceptable if it was scored as 2 or 3.

## **In-plane trajectories extraction**

The segmentation type was selected for each series based on the expert's decision. The greatest connected component of each segmentation mask was selected (using the MATLAB Image Processing Toolbox) and its center of mass was calculated for each image.

Then, the axial slice was superimposed onto the sagittal images, and vice versa, using positional and orientation data retrieved from the DICOM files. The portions of masks lying inside the slices' intersection volume (referred to as IS-masks) were computed, along with their respective centers of mass.

Additionally, for the sagittal slices, the extremity of the condylar head was calculated. For this, the full segmentation masks were rotated to the principal component space (MATLAB PCA implementation). Only 5% of points with the smallest first principal component were kept and then rotated back into the image space. The average of these points was regarded as the condyle's top point. This approach enhances tracking consistency by focusing on the upper regions of the condyles, as their lower boundaries are not well-defined.

## **Head motion registration**

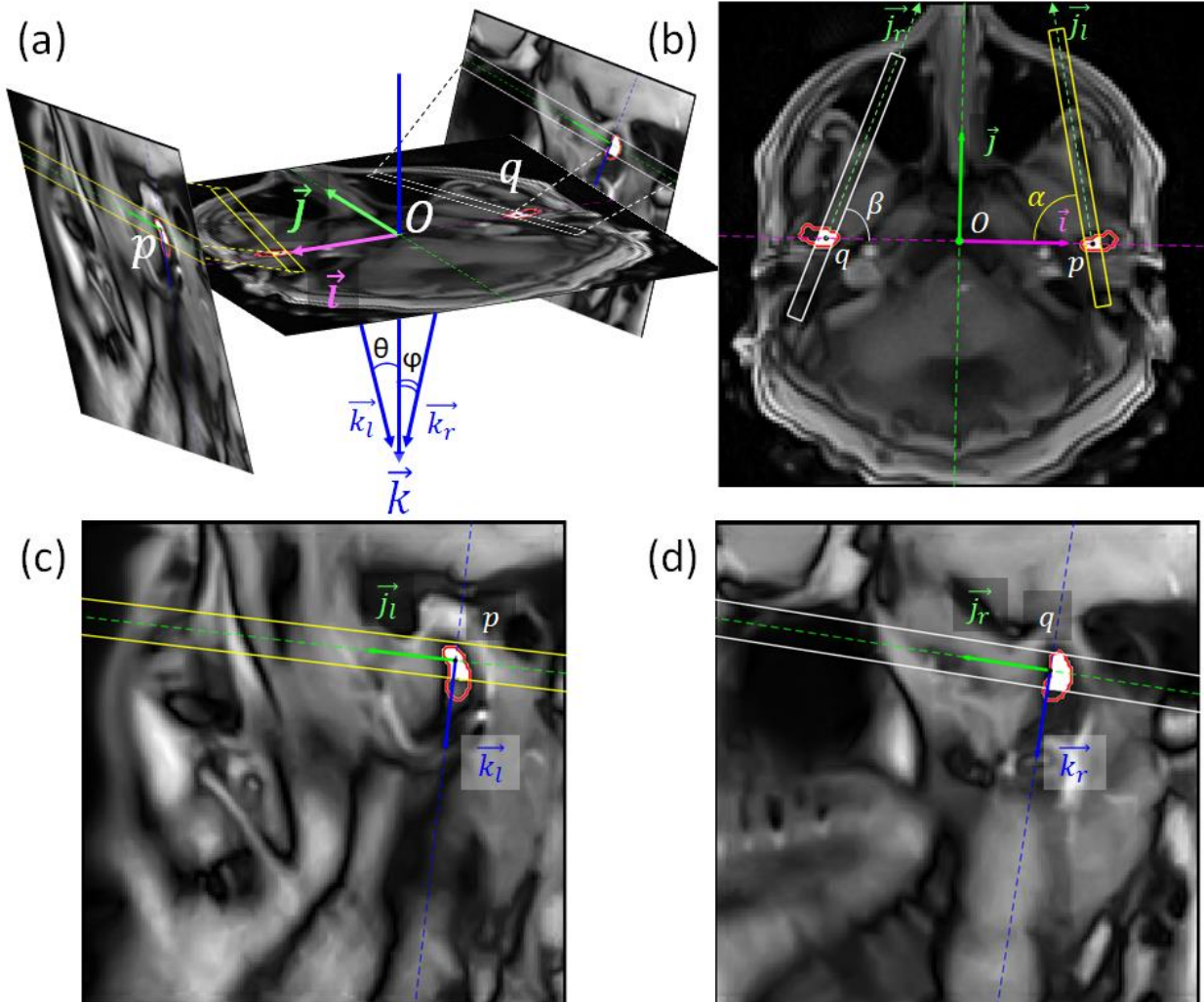
The extracted trajectories were rotated and translated to best align with the initial head position. For this purpose, five to nine extraoral regions (including the ear canal, inferior oblique eye muscle, segments of the temporal bone, and well-visible brain structures in sagittal slices, as well as the ears, notable nasal features, and brain structures in axial slices) were automatically segmented for each frame of the series using the Segment Anything model [27]. From these, the three to five most stable masks were manually selected for each series.

A median filter and a low-pass filter with a cutoff frequency of 1 Hz were then applied to the centers of mass of the retained masks. A rigid transformation was calculated for each frame by minimizing the Procrustes distance based on the computed centers of mass (using the MATLAB Statistics and Machine Learning Toolbox) between each frame and the first frame of the sequence. The mean distance between the in-plane condylar trajectories before and after registration  $\langle d_{reg-nonreg} \rangle$  was calculated to assess intra-sequence motion for each subject.

Additionally, to roughly estimate the inter-sequence motion and the overall mobility of the subject, slices with the same coordinates as the dynamic axial and sagittal slices were extracted from the 3D SPACE image acquired at the beginning of the protocol. These images were visually compared to the dynamic images in the intercusp position (ICP).

## 2D trajectories projection onto the 3D coordinate system

This step comprised the construction of the 3D coordinate system with the origin  $O$  and the orthonormal basis  $(\vec{i}, \vec{j}, \vec{k})$  (as shown in Fig. 3a) and projection of the 2D trajectories to the selected coordinate system.



**Fig. 3.** Illustration of the mutual slice orientation and the coordinate system choice. The arrows  $\vec{i}$ ,  $\vec{j}$ ,  $\vec{k}$  denote the selected orthonormal basis,  $O$  is the origin, and the points  $p$  and  $q$  show the intersection of the axis  $\vec{i}$  with the sagittal slices. The red contours show the predicated condyles' masks and the white area inside them corresponds to the IS-

masks. (a) The global 3D view. (b) The axial slice. Yellow rectangle – left sagittal slice, white rectangle – right sagittal slice. (c) Left sagittal slice. Yellow lines – axial slice. (d) Right sagittal slice. White lines – axial slice.

The origin  $O$  was defined as the center of mass of the left and right IS-masks from the axial images in the ICP. The unitary vector  $\vec{i}$  was selected to be parallel to the line traversing these mass centers from right to left (see Fig. 3b). The unitary vector  $\vec{j}$  was chosen to lie in the oblique axial plane, be perpendicular to  $\vec{i}$  and directed from posterior to anterior. And, finally, the unitary vector  $\vec{k}$  was perpendicular to both  $\vec{i}$  and  $\vec{j}$  and going from superior to inferior.

The 2D trajectories from the axial slice were projected directly to  $\vec{i}$  and  $\vec{j}$  directions. As for the 2D trajectories derived from the sagittal slice, the origin points—representing the ICP and determined from the axial slice—were identified first:  $p$  (for the left sagittal slice) and  $q$  (for the right sagittal slice). Following this, the 2D trajectories were projected on directions  $\vec{j}_l, \vec{k}_l, \vec{j}_r, \vec{k}_r$ , where  $j_{l,r}$  is directed parallel to the axial plane and  $k_{l,r}$  lies in the sagittal plane, perpendicular to  $j_{l,r}$ , with  $l$  and  $r$  denoting the side (left and right) – see Fig. 3b-3d for the illustration. Subsequently, the angles  $\alpha$  and  $\beta$  (see Fig. 3b) and  $\theta$  and  $\varphi$  (see Fig. 3a) were calculated. Finally,  $\vec{j}_l, \vec{k}_l, \vec{j}_r, \vec{k}_r$  projections were projected to the  $(\vec{j}, \vec{k})$  basis.

The trajectories' projections were post-processed with median and adaptive low-pass filtering, as described in [23]. For this, for each of the planes and sides, opening and closing intervals were found using the procedure based on the velocity analysis (described in [23]). A motion cycle was defined as the time interval between two consequent ICPs.

### 3D trajectories calculation

If there was no head motion, and if the opening-closing movements were perfectly reproducible, the  $j$ -coordinates of IS-masks from the axial slice should be equal to those from the sagittal slices. In this case, the 3D trajectories computing would be a trivial task. However, human subjects tend to displace their head and do not succeed in exactly reproducing the same movement for each opening and closing cycle. So, the method consisted of attempting to identify the optimal repetition and coordinate systems, and to merge information from both the axial and sagittal slices.

Each motion cycle from the axial plane was temporally adjusted to each cycle from the sagittal plane. For doing so, the IS-masks'  $j$ -projections were normalized to have an amplitude of 1, temporally stretched using dynamic time warping (DTW, MATLAB Signal Processing Toolbox), and de-normalized so return to the real amplitude values. The

pair of one axial and one sagittal cycle that demonstrated the smallest difference between the temporally adjusted IS-masks  $j$ -coordinates, was selected as the best match and was used for the further processing. The calculated DTW transformation was applied to all projections. The resulting curves were smoothed with MATLAB smoothing splines (with a smoothing parameter of 0.1).

The trajectory  $i$ -projection was extracted from the axial plane,  $k$  – from the sagittal plane, and  $j$  was calculated as an average from the axial and the sagittal plane. This was done to minimize possible errors due to incorrect slice placement. Finally, the coordinate system was re-adjusted once again, so that both condyles have zero  $j$ - and  $k$  projections at the beginning of the cycle.

## **Quality estimation**

Despite the minimization of the inconsistencies, some imprecisions were still present. Three possible major sources of these errors are the insufficient reproducibility of the movement, residual head motion, and imprecise slice placement.

If motion was not fully compensated, the initial and final trajectory points would differ. Therefore, residual head motion was quantified as the distance between the initial and final ICP  $d_{init-fin}$ . Slice placement accuracy was assessed by the difference in the  $k$ -projection between the left and right condyles in the ICP,  $\Delta k_{L-R}$ . Finally, the distance between the trajectories calculated using only  $j$ -projection from the sagittal slice, or only  $j$ -projection from the axial slice,  $\Delta j_{AX-SAG}$ , was used to characterize both imprecise slice placement and any mismatch between the axial and sagittal cycles.

# **RESULTS**

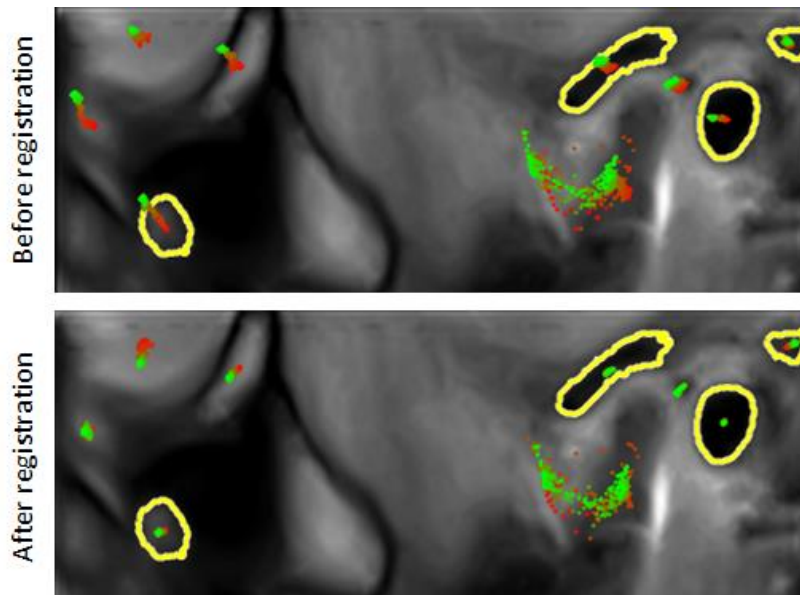
## **Segmentation**

The video series with the segmented condyles are presented in [28], and a detailed summary of the quantitative metrics and expert's scores is provided in Online Resource 1. For the axial images, both inter-subject and fine-tuned strategies resulted in good segmentation quality (average score of 2.8 for AX-IS and 2.7 for AX-FT). The most frequent cause of incorrect segmentation was the partial volume effect from the mandibular ramus (as discussed in [23]). For the

sagittal slices, the best model was SAG-FT-20 (with an average score of 2.6), followed by SAG-FT-45 (score 2.48). SAG-IS-20 demonstrated the worst results due to tracking errors (score 2.2).

Among the selected segmentations, 18 videos from the axial plane were evaluated with a score of 3, and two videos received a score of 2. For the left sagittal plane, 19 videos scored 3, and one scored 2. For the right sagittal plane, 17 videos received a score of 3, and three received a score of 2. The Dice score for the selected segmentations was  $0.84 \pm 0.07$  (precision  $0.74 \pm 0.09$ /recall  $0.97 \pm 0.05$ ) for the axial slices and  $0.89 \pm 0.04$  (precision  $0.83 \pm 0.07$ /recall  $0.96 \pm 0.05$ ) for the sagittal slices, and the DCM (measuring the distance between the center of mass of predicted and ground truth masks) was  $0.65 \pm 0.37$  mm for the axial slices and  $1.09 \pm 0.70$  mm for the sagittal slices.

### **Head motion registration**



**Fig. 4.** Example of head motion registration results (subject 18). The retained extraoral regions are delineated in yellow. The centers of mass of the segmented regions are depicted using a color gradient from red (indicating the start) to green (indicating the end). Noticeable compensation for global pitch movement is observed.

In several subjects, significant head motion was detected, with pitch movement being the predominant motion type. The detected motion in the left-right direction was negligibly small. In certain cases (e.g., subject 7), the displacement of extraoral points was correlated with condylar movement, consistently returning to the same ICP after each cycle.

Conversely, in other subjects (e.g., subject 18), the motion appeared more global, with extraoral points continuing to shift in the same direction after each opening-closing cycle. An example of this motion registration is shown in Fig. 4.

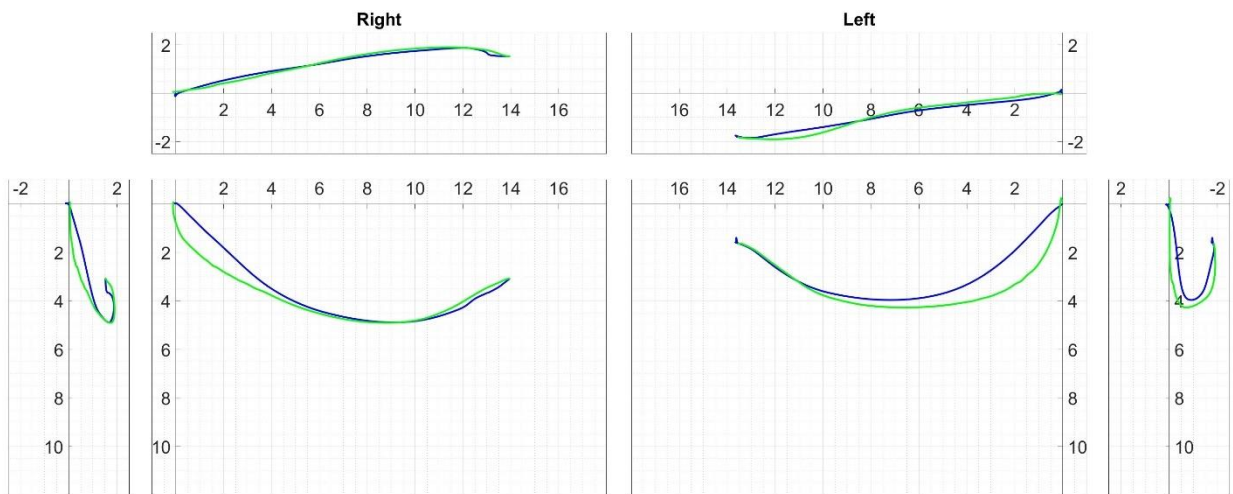
Subject	Side	Min % on AX	Min % on SAG	$\langle d_{reg-nonreg} \rangle_{SAG}$ , mm	$\langle d_{reg-nonreg} \rangle_{AX}$ , mm	$d_{inter-seq}$	$d_{init-fin}$ , mm	$\Delta j_{AX-SAG}$ , mm	$\Delta k_{L-R}$ , mm
1	L	No simultaneous sagittal planes imaging							
	R								
2	L	No simultaneous sagittal planes imaging							
	R								
3	L	67	21	0.28	0.39	N	0.12	0.64±0.42	0.96
	R	75	25	0.61			0.16	0.35±0.22	
4	L	32	60	0.56	0.28	N	0.19	1.41±0.79	4.03
	R	77	18	0.64			0.19	1.08±0.87	
5	L	78	15	0.4	0.35	Y	0.7	0.63±0.35	-0.27
	R	81	17	0.26			0.37	0.30±0.25	
6	L	81	28	No full opening-closing cycle					
	R	36	13						
7	L	30	38	1.83	0.33	N	2.42	0.54±0.32	-0.33
	R	61	38	1.78			2.84	2.04±0.73	
8	L	52	35	0.65	0.38	Y	0.86	0.57±0.40	0.57
	R	74	30	0.54			0.58	0.89±0.62	
9	L	59	0	Masks in the sagittal plane are out of the axial plane					
	R	57	0						
10	L	69	14	2.21	0.96	Y	1.25	2.88±2.35	-1.53
	R	52	29	1.71			0.97	2.11±3.62	
11	L	73	10	The right condyle in the sagittal plane is out of the axial plane					
	R	68	0						
12	L	61	26	1.14	0.18	Y	0.59	2.62±0.90	-1.61
	R	79	55	0.81			0.71	0.48±0.23	
13	L	56	0	Condyles in the sagittal plane are out of the axial plane					
	R	62	0						
14	L	44	42	0.78	0.26	N	0.84	0.8±0.74	-0.12
	R	57	19	0.74			0.25	0.79±0.53	
15	L	33	6	The right condyle in the sagittal plane is out of the axial plane					
	R	64	0						
16	L	83	38	1.09	0.33	N	0.82	0.58±0.47	-0.63
	R	52	39	0.87			0.97	1.01±0.29	
17	L	33	48	1.1	0.41	N	0.57	1.57±2.02	-4.05
	R	59	48	0.8			0.64	0.58±0.47	
18	L	29	16	2.56	0.55	Y	0.68	0.84±0.82	-2.43
	R	32	20	2.55			0.47	2.3±1.44	
19	L	73	46	0.16	0.07	N	2.52	1.72±0.50	-0.4
	R	75	28	0.16			4.17	1.23±0.52	
20	L	29	11	0.68	0.16	Y	0.29	0.16±0.15	-2.18
	R	46	23	1.05			0.19	0.49±0.56	

**Table 1.** Motion and quality metrics calculated for each extracted trajectory.

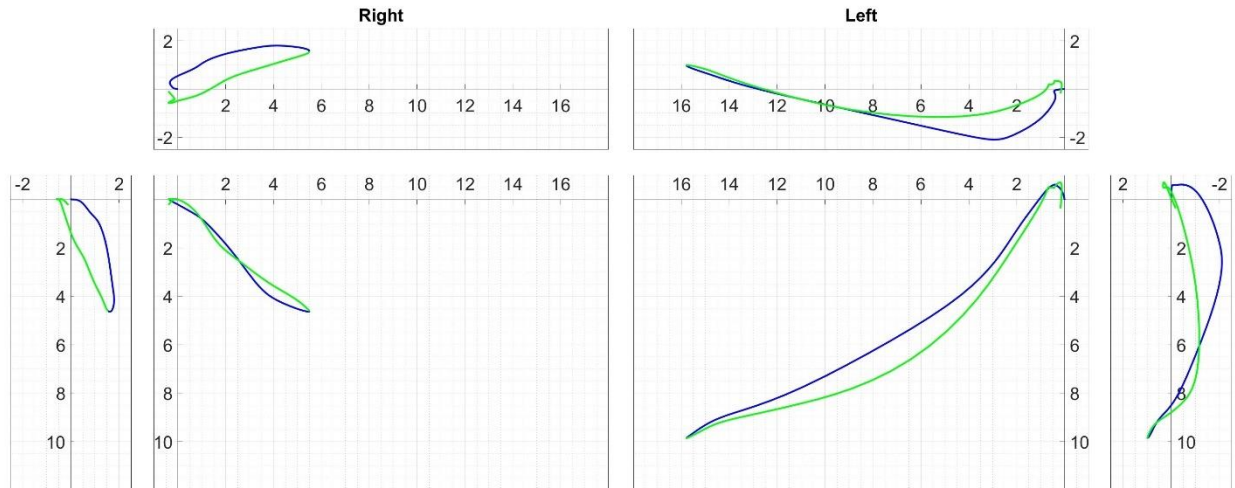
The registration resulted in a displacement of the condylar trajectory ranging from 0.16 to 2.55 mm in the sagittal plane and from 0.07 to 0.96 mm in the axial plane (see Table 1). Additionally, some subjects were found to show differences in position between the static and dynamic acquisitions (see Table 1). Subjects who demonstrated inter-sequence motion also had slightly higher  $\langle d_{reg-nonreg} \rangle$  values averaged across all planes (0.64 mm on average for subjects without inter-sequence motion, compared to 0.92 mm for those with inter-sequence motion).

## **Trajectories**

The plots of the automatically calculated motion phases are presented in Online Resource 2 and all computed trajectories are provided in Online Resource 3. It should be noted that some subjects were excluded at different stages of the analysis for the reasons given in Table 1. Examples of the trajectories extracted from real-time MRI are provided in Fig. 5 and 6.



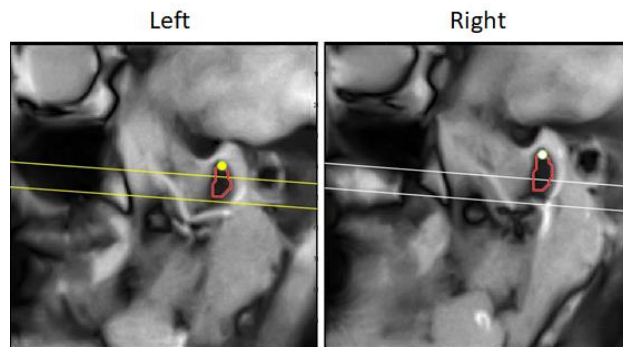
**Fig. 5.** A typical example of extracted mandibular condyles' 3D trajectories during opening-closing motion (subject 3). The blue curves correspond to openings and the green curves – to closings.



**Fig. 6.** An example of asymmetric mandibular condyles' 3D trajectories during opening-closing motion (subject 12). The blue curves correspond to openings and the green curves – to closings.

The trajectory quality metrics are summarized in Table 1. The distance between the initial and final ICP coordinates ranged from 0.12 mm to 4.17 mm. Larger values were observed when the selected best-match cycle ended with an incomplete closing, which some subjects performed in anticipation of the next opening movement (e.g., subject 19). The mean  $d_{init-fin}$  value excluding the incomplete cycles was 0.56 mm.

The difference in the k-projection in the ICP at the beginning of the selected cycles ranged from -4.05 mm to 4.03 mm (-0.61 mm on average, with the mean of the absolute values of 1.47 mm). An example of asymmetrically placed axial slice is provided in Fig. 7.



**Fig. 7.** Illustration of an asymmetric axial slice placement. The yellow and the white lines depict the axial slice position in the left and the right sagittal slices, correspondingly, the red curves are the segmentation masks, and the yellow and the white markers point to the top condyle point. The intercuspal position is displayed; however, the right condyle is substantially higher to the axial slice than the left condyle.

Finally, the average distance between the trajectories calculated using only j-projection from the axial plane, or only that from the sagittal plane, varied from 0.16 to 2.88 mm. The greater values were observed when a significant displacement was noticed during the motion analysis (e.g. subject 18), or when the axial slice was placed much lower than the condylar heads (e.g. subject 10). The latter case corresponds to lower values of the minimal percent on sagittal slice.

## DISCUSSION

We demonstrated that it is possible to compute 3D condylar trajectories from two 2D real-time MRI sequences, one being placed in the oblique axial plane, and one covering 2 oblique sagittal planes. The appearance of the trajectories is in agreement with the literature [4,9,10].

It was shown that the condyles in the axial plane can be automatically segmented with a good segmentation quality. The sagittal images, however, required some fine-tuning. This issue is related to the considerably different contrast of the condyles, as illustrated in Fig. 2. A greater training set should improve the quality of the automatic segmentation in the sagittal plane. Therefore, the proposed trajectories extraction algorithm was almost automated, with the realistic potential to be fully automatic. For both planes, the segmentation algorithm tended to over-segment the condyles.

Head motion registration significantly reduced the displacement of extraoral points in some subjects, potentially enhancing the quality of the resulting trajectories. The predominant detected motion type was the pitch movement (extension-flexion), in agreement with the literature [29,30]. While the reliability of individual segmentations was not explicitly assessed in this study, the redundancy in the centers of mass from the masks is expected to reduce the overall registration error.

However, the method has multiple limitations. Firstly, the interslice mapping was based on the j-projection. However, if condyles move mostly out of the Frankfurt plane (like for subject 11), the method is not applicable. In this case, the orientation of the axial plane should be changed. Moreover, the up-and-down movement can change the condyles' shape in the axial plane and thus affect the center of mass position. Ideally, a biomechanical model using 3D segmentation of the mandible should be developed to address this issue. The work in this direction is ongoing.

Additionally, more attention should be paid to the placement of the axial plane, which was visibly asymmetric to the anatomical structures for greater absolute values of  $\Delta k_{L-R}$ . In this case, the trajectories may be artificially asymmetric, while the actual movement was symmetric. The axial slice should not be placed too low, since in this case the  $j$ -projections extracted from the axial and sagittal planes become too different potentially affecting the method's accuracy. Similarly, an asymmetric placement of sagittal planes can greatly impact the symmetry of the trajectories. Paying attention to both  $\Delta k_{L-R}$  and  $\Delta j_{AX-SAG}$  could allow the quantitative control of the slice placement.

Another serious challenge is related to head motion. While axiographs move along with the head, MRI remains static. Head motion led to the exclusion of subjects 9, 13, and 15 since, during the acquisition of the sagittal slice the condyles were not within the axial slice anymore. The motion that remained due to incomplete motion compensation also distorted the extracted trajectories, reflected in high distance between the initial and final position. However, this parameter might be high due to other reasons (e.g., the presence of undiagnosed TMD or uncompleted closing). To minimize motion, additional head fixation could be applied. Moreover, in contrast to the protocol utilized in this study, the real-time sequences could be run immediately one after the other, and at the beginning of the imaging protocol. This could also improve the reproducibility of the opening-closing movement.

This study revealed several critical factors that need attention to ensure reliable extraction of mandibular condyle trajectories. Implementing automatic, real-time computation of the proposed metrics would allow for immediate quality control, enabling rapid assessment of whether a repeated acquisition is necessary. This would make it possible to assess key characteristics of the extracted trajectories, such as length, shape, and symmetry [31,32]. Although the accuracy of this method is likely lower than that of state-of-the-art devices [10], MRI-based trajectory computing could be prescribed to patients requiring an MRI exam, as an addition to the conventional protocol.

To conclude, this study is the first to extract 3D trajectories of mandibular condyles, which are relevant clinical information, directly from MRI. We demonstrated the feasibility of their automatic computing from 2D real-time MRI. While there are factors that can compromise the method's accuracy—such as head motion, asymmetric slice placement, and imperfect movement reproducibility—these influences are manageable. Therefore, this method could serve as a complementary tool for patients undergoing MRI for the investigation of the temporomandibular joint soft tissue anatomy, enabling an all-in-one examination.

## COMPLIANCE WITH ETHICAL STANDARDS

**Competing Interests.** The authors have no relevant financial or non-financial interests to disclose.

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**Ethics approval.** The data was acquired under two approved ethical protocols: “METHODO” (ClinicalTrials.gov Identifier: NCT02887053, approval: CPP EST-III, 08.10.01) and its successor “EDEN” (ClinicalTrials.gov Identifier: NCT05218460, approval: CPP SUD-EST IV, 26.07.21). This study was performed in line with the principles of the Declaration of Helsinki. The sponsor of this study was the CHRU de Nancy (Department of Methodology, Promotion, Investigation—MPI).

**Informed consent.** All participants provided written informed consent.

**Data availability statement.** The raw experimental data are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. All intermediate results are available in Figshare with the identifier <https://doi.org/10.6084/m9.figshare.25846300.v1> and in the article supplementary information.

## AUTHOR STATEMENT

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## **Supplementary Information**

ESM\_1.pdf: Detailed results of quantitative and qualitative evaluation of the segmentation quality.

ESM\_2.pdf: Results of the automatic motion phase detection.

ESM\_3.pdf: The calculated 3D trajectories for all subjects.