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CLINICAL RESEARCH

Symmetry of mandibular movements: A 3D electromagnetic articulography technique applied on asymptomatic participants

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ABSTRACT

Statement of problem. Asymmetries in mandibular movements (MMs) can be found in patients with some temporomandibular joint disorders, condylar fracture, or after orthognathic or orthodontic surgery. Quality and symmetry of the MMs should be recorded and analyzed. However, methods for this purpose are limited.

Purpose. The purpose of this clinical study was to determine the symmetry of MMs on asymptomatic participants by applying an innovative technique based on 3D electromagnetic articulography.

Material and methods. The symmetry of MMs was studied in 16 fully dentate participants (8 men and 8 women). A 3D electromagnetic articulograph was used to register MM by placing a sensor on the interincisal midline of the mandible. The border movements related to the frontal (FP), sagittal (SP), and horizontal (HP) polygons of the Posselt envelope of motion were recorded, as well as masticatory movements. Digital data processing was applied to calculate the trajectory and ranges of mandible displacement, area of the right and left sectors of FP and HP, similarity index between the right and left sectors of FP and HP, and orientation of the individualized masticatory cycles. The Shapiro-Wilk statistical test was used to determine the normality of the sample. To compare the characteristics of the right and left sectors of the polygons, a paired-samples *t* test (normal distributions) and Wilcoxon test for paired samples (non-normal distributions) were applied (α=.05).

Results. No statistically significant differences were found between the right and left sectors of the frontal and horizontal polygons in terms of trajectory (FP, *P*=.408; HP, *P*=.417), ranges of movement (FP, *P*=.736; HP, *P*=.650), areas (FP, *P*=.736; HP, *P*=.233), or orientation of the cycles (*P*=.506). The similarity index between the morphology of the right and left sectors of the polygons was 68 ±12% for the FP and 67 ±11% for the HP. The areas, trajectories, and ranges had similar values, but they had a different morphology on each side of the polygons. Regarding masticatory cycles, a balanced distribution was observed in terms of their orientation.

Conclusions. The technique used allowed the assessment of symmetry of MM on asymptomatic participants. The evaluated parameters maintain similar values at both left and right sides; however, a different morphology of the trajectories and areas was observed. (J Prosthet Dent 2021;125:746-52)

Mandibular movements (MMs) are produced through a complex series of interrelated 3D activities of rotation and translation. They are determined by the combined and simultaneous actions of the 2 temporomandibular joints (TMJs).[1] When the mandible is displaced by the most external part of its range of motion, limits known as border movements are observed. The amplitude of the opening border movements—anterior, posterior, or lateral—is limited essentially by the ligaments and morphology of the TMJs. The superior contact border movements are determined by the occlusal and incisor surfaces of the teeth.[1]

Functional movements are not considered border movements because they are not determined by an external restriction, but rather by the

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Clinical Implications

Previous studies have suggested differences between the right and left ranges of mandibular movement that distinguish asymptomatic participants from patients with temporomandibular joint disorders. The methodology used should improve the understanding of the symmetry of mandibular movements. It can suggest future clinical recommendations that would favor the symmetry of these movements in patients with different clinical conditions.

conditional responses of the neuromuscular system.[1] Generally, they occur within the border movements and are considered free movements.[1] During mastication, the mandible describes a downward movement from maximum intercuspation (PMI) until it reaches the desired opening. Then, it moves to the side in which the food bolus is located and rises. When approaching maximum intercuspation, the bolus is masticated between the opposing teeth. In the last millimeter of closing, the mandible quickly returns to PMI.[1]

MMs have been analyzed extensively, most recently for the study of the masticatory system, and have also been used as a clinical variable in the diagnosis of different temporomandibular joint disorders (TMDs).[2] A consensus suggests that the quality and symmetry of MM must be recorded and analyzed.[3,4] However, methods to achieve this are limited. A millimeter ruler has been used to measure laterotrusive ranges, protrusive ranges, and maximal opening deviations to compare right and left displacements of the mandible.[5-8] With the same purpose, a kinesiograph (Sirognathograph; Siemens) has been used to measure laterotrusive, protrusive, maximal opening ranges, and lateral and anterior guidance.[9,10] Those techniques are limited to the analysis of ranges or angles and do not allow the study of the trajectories and areas described by the border and functional movements of the mandible.

Electromagnetic articulography (EMA) is an innovative, safe, and noninvasive technique to register MM. Its working principle is based on the use of electromagnetic induction to determine distances. This equipment was originally devised to register movements of the speech organs during speech production.[11-13] Fuentes et al[14-16] used a 3D EMA to analyze the characteristics of the masticatory cycles of asymptomatic participants with normal occlusion. Hoke et al[17] used an articulograph to determine micromovements of dental prostheses during mastication. Compared with other methods used to study MM, EMA systems allow more natural movements because they do not have restrictive components attached to the patient's head and they also reach high temporal (up to 1 kHz) and spatial (up to 0.3 mm) precision.[15,18] In several studies, the data collected by articulography are digitally processed to obtain kinematic parameters such as trajectories, displacement ranges, and distances.[14-17] Digital processing of 3D coordinates obtained with this technology, at high sample frequency and high precision, offers the possibility of improving existing methods.

Previous studies have reported asymmetries regarding MMs in patients with TMDs, patients with condylar fracture, and patients who had received orthognathic or orthodontic surgery.[8-10,19,20] In addition, the prognosis has been reported to differ according to the patient's age. Elderly patients with asymmetric MMs tend to get worse if they do not undergo treatment, which suggests monitoring is advisable. The purpose of this clinical study was to determine the symmetry of MMs on asymptomatic participants by applying a technique based on 3D electromagnetic articulography under the hypothesis that even asymptomatic individuals do not present perfect symmetry regarding border and functional MM.

MATERIAL AND METHODS

A 3D electromagnetic articulograph (AG501; Carstens Medizinelektronik) was used to record mandibular border and functional movements. The recording protocol applied was based on that developed by Fuentes et al.[14-16,18] The border movements recorded were based on those proposed by Okeson.[1] Each clinical examination and experimental procedure was carried out by the same researchers (M.F.L., P.C.).

Sixteen participants were included in this study (8 men and 8 women; 22 ±3 years old), all students of the Faculty of Dentistry at Universidad de La Frontera. The participants were dentate, with normal occlusion, had not received orthodontic treatment, suffered trauma, or received major maxillofacial surgery and did not wear a prosthesis with a metal connector. A screening test as recommended by the American Academy of Orofacial Pain (1990)[21] was used to exclude individuals with signs and symptoms of TMJ disorders. Participants with occlusal interferences, malocclusions such as open anterior occlusion, or reverse articulation were excluded, as well as those with orthodontic appliances or muscular asymmetry. This investigation received ethics committee approval nr. 125_18, Universidad de La Frontera. Sample size was computed a priori by using a software program (G*Power 3.1; Heinrich-Heine-Universität).[22]

The experimental procedure was carried out in the Laboratory of Oral Physiology at the Research Center in Dental Science in the Faculty of Dentistry, Universidad de La Frontera (Temuco, Chile). The previously calibrated articulographic sensors were fixed to the surface of the

Figure 1. Position of sensors. A, Reference sensors placed on mastoids and glabellae (*gray arrows*) and intraoral active sensor (*yellow arrow*) in participant at rest. B, Position of active sensor (*yellow arrow*) in mouth.

Table 1. Mandibular border movements

Polygon	Right	Left
Frontal polygon	Mandibular displacement with tooth contact from PMI to maximum right laterality. From position of maximum right laterality, movement of right lateral opening until reaching MO.	Mandibular displacement with tooth contact from PMI to maximum left laterality. From position of maximum left laterality, movement of left lateral opening until reaching MO.
Horizontal polygon	Mandibular displacement with tooth contact from CR to maximum right laterality followed by protrusive displacement to left until reaching MPC.	Mandibular displacement with tooth contact from CR to maximum left laterality followed by protrusive displacement to right until reaching MPC.
Polygon	**Anterior**	**Posterior**
Sagittal polygon	Mandibular displacement with tooth contact from PMI to MPC followed by anterior opening until reaching MO.	Mandibular displacement with tooth contact from PMI to CR followed by posterior opening until reaching MO.

CR, centric relation; MO, maximum opening; MPC, maximum protrusion with contact; PMI, maximum intercuspation.

skin and gingiva by using tissue adhesive (Epiglu; Meyer-Haake GmbH) (Fig. 1). An active sensor was placed on the interincisal midline of the mandible to register the movement of the mandible. Three reference sensors were placed to obtain the position of the mandible relative to the skull.

First, a reference recording was conducted. During this recording, the participant was instructed to look forward with the head in an upright position and the Frankfort plane parallel to the floor. The anatomic planes were aligned with the axes of the measurement area. This recording was used subsequently to define the frontal, sagittal, and horizontal anatomic planes in the recordings.

With the participant seated in an upright position, 3 repetitions of the border movements listed in Table 1 were recorded to obtain the frontal (FP), horizontal (HP), and sagittal (SP) Posselt polygons.[1] Additionally, mastication of 3.7 g of peanuts was registered from PMI, with the peanuts placed between the tongue and the palate, to the first swallow. The orientation (right or left) of these cycles was analyzed posteriorly.

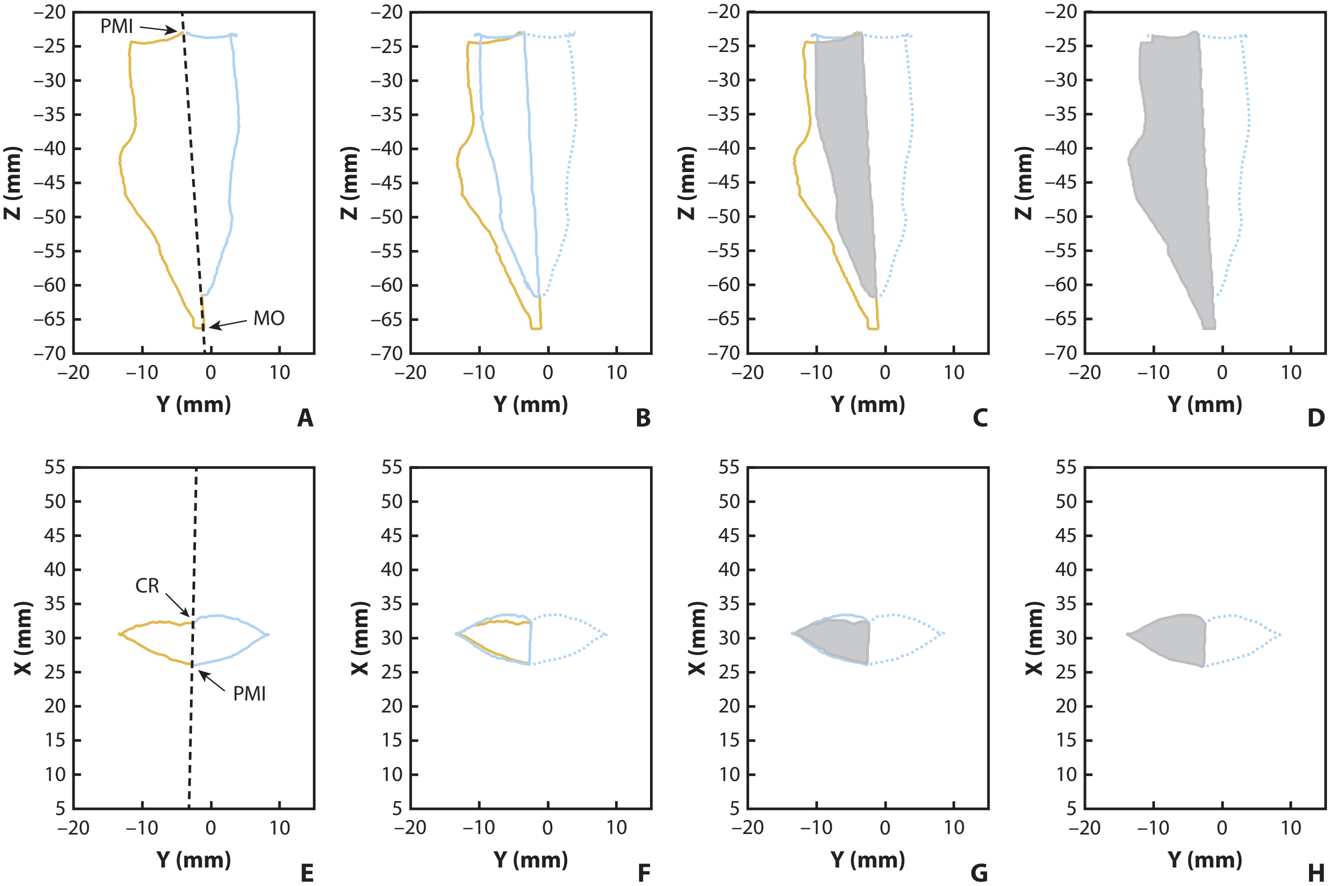

Figure 2. Border movements of participant (output of data processing in Matlab). Frontal plane: A, Division of polygon into right (*blue*) and left (*orange*) sectors. B, Mirrored and superposition of left sector over right. C, Area of intersection between right and left sectors (*gray*). D, Area of union between right and left sectors (*gray*). Horizontal plane: E, Division of polygon into right (*blue*) and left (*orange*) sectors. F, Mirrored and superposition of left sector over right. G, Area of intersection between right and left sectors (*gray*). H, Area of union between right and left sectors (*gray*).

The resulting files from each articulographic recording were processed by using an engineering software program (Matlab R2019a; MathWorks), for which specific algorithms were programmed. To analyze the symmetry of the mandibular border movements, FP and HP were divided into 2 sectors (right and left) limited by SP, as marked with a dotted line in Figure 2. The mid-sagittal plane was defined by the points PMI, MO, and MPC from the recordings of the border movements in the SP, as shown in Figure 2. The following parameters were calculated: mandibular trajectory to the right and left, range of mandibular displacement to the right and left, area in the right and left sectors of FP and HP, and the similarity index between the right and left sectors of FP and HP.

To calculate the similarity index, SP was used as a reference to mirror the left sector of each polygon over the right sector. Then, the areas of intersection and union were determined, as shown in Figure 2. The similarity index was obtained by using equation 1, where the term $(P_{der} \cup P_{izq})$ corresponds to the area of union between the right and left sectors of each polygon and the term $(P_{der} \cap P_{izq})$ corresponds to the area of intersection.

$$\text{Similarity} = \left(1 - \frac{(P_{der} \cup P_{izq}) - (P_{der} \cap P_{izq})}{(P_{der} \cup P_{izq})}\right) \times 100\ \% \qquad (1)$$

The orientation of the individualized masticatory cycles was assessed. In this case, the projection of each masticatory cycle on the frontal plane was plotted as shown in Figure 3, and the orientation of each cycle (right or left) was determined. Finally, the percentage of cycles with right orientation and the percentage of cycles with left orientation were determined.

The data were analyzed by using a statistical software program (SPSS Statistics v17.0; SPSS Inc). After a descriptive statistical analysis, the Shapiro-Wilk test was used to determine the normality of the data. To compare the characteristics of the right and left sectors of the polygons, a paired-samples *t* test (normal distributions) and the Wilcoxon test for paired samples (non-normal distributions) were used (α=.05).

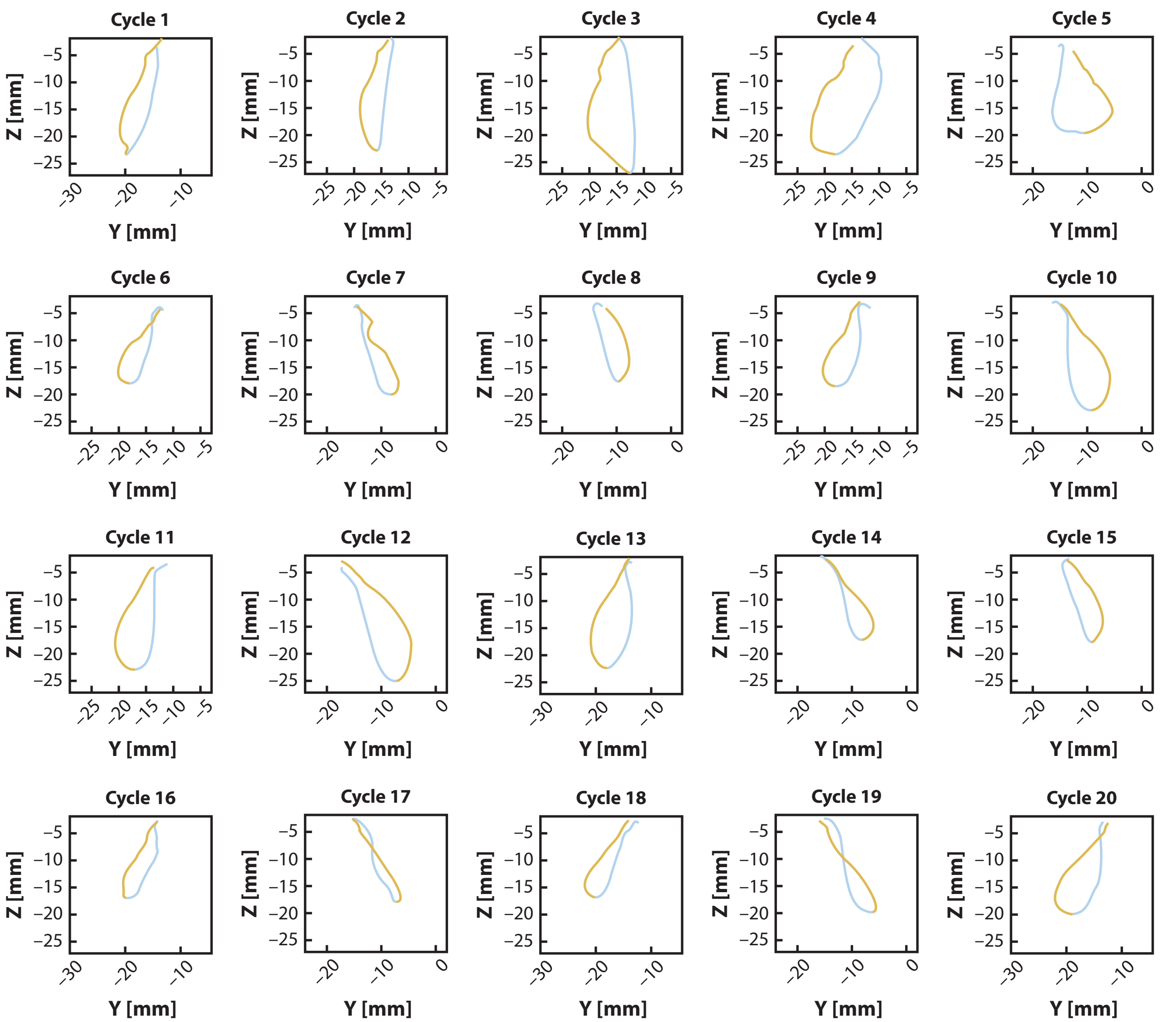

Figure 3. Masticatory cycles of participants. Descent in *orange* and ascent in *blue*. Cycles 1, 2, 3, 4, 6, 9, 11, 13, 16, 18, and 20 are moving to right. Cycles 5, 7, 8, 10, 12, 14, 15, 17, and 19 are moving to left.

RESULTS

The frontal and horizontal polygons were analyzed according to the sequence shown in Figure 2. Equation 1 was applied to obtain the similarity index. In addition, the graphic representation of the individualized masticatory cycles on the frontal plane was plotted as shown in Figure 3, from which the percentages of cycles with right orientation and left orientation were extracted.

No statistically significant differences were found between the right and left sectors of FP and HP in terms of mandibular trajectory (FP, *P*=.408; HP, *P*=.417), ranges of laterality movement (FP, *P*=.736; HP, *P*=.650), area of the polygons (FP, *P*=.736; HP, *P*=.233), or orientation of the cycles (*P*=.506). The average values of the contrasted variables are shown in Table 2. The similarity index between the right and left sectors was 68 ±12% for FP and 67 ±11% for HP.

DISCUSSION

The results of this clinical study supported the hypothesis that even asymptomatic individuals do not present perfect symmetry regarding border and functional MM. Mandibular movements are limited by the ligaments and joint surfaces of the TMJ, as well as by the morphology and alignment of the teeth.[1] Asymmetries between the superior contact border movements are related to asymmetries on the occlusal surface, and asymmetries between the opening movements to asymmetries in the morphology of the TMJ and the musculature.[1] The results of the present study revealed

Table 2. Dimensions of polygons and orientation of masticatory cycles

Figure	Parameter	Right	Left
Frontal polygon	Trajectory	80 ±11 mm	79 ±11 mm
	Range	9 ±2 mm	9 ±2 mm
	Area	211 ±89 mm^2	218 ±81 mm^2
Horizontal polygon	Trajectory	42 ±9 mm	42 ±10 mm
	Range	9 ±2 mm	9 ±2 mm
	Area	47 ±20 mm^2	44 ±20 mm^2
Masticatory cycles	Orientation	54 ±25%	46 ±25%

that, in asymptomatic participants, the mandibular border movements in the frontal and horizontal planes did not present significant differences in terms of ranges, trajectories, or areas. The similarity index was 68 ±12% for the frontal plane and 67 ±11% for the horizontal plane. These values suggest that the evaluated parameters were similar; however, a different morphology was observed for the areas on each side of the polygons, which would help to explain the differences of around 30% in similarity. Regarding the functional movements, a balanced distribution was found with respect to the orientation of the masticatory cycles because the percentages of cycles with right and left orientation were similar (both close to 50%). However, some individuals showed a preference for a side during some of the 3 mastication recordings, which would help explain the standard deviation close to 25%.

Previous studies have analyzed symmetry parameters of MM in participants without TMJ disorders. Ferrario et al[10] evaluated the symmetry of MM by analyzing the sagittal slope of the laterotrusive and protrusive movements recorded by kinesiography (Sirognathograph; Siemens). They reported an asymmetry index for the measured angles of 16% in the frontal plane and 11% in the horizontal plane. The differences with the asymmetry values observed in the present study could be from differences between the analyzed parameters.

Other studies have analyzed the symmetry of MM in different clinical conditions.[3,6,8,9,20] In the case of patients with condylar fracture, symptoms of dysfunction in the masticatory system have been observed.[6] Measurements with a millimeter ruler have revealed asymmetry of MM between the fractured and nonfractured sides.[6] In patients with muscle pain associated with craniomandibular disorder, the MM recorded by kinesiography (Sirognathograph; Siemens) have revealed differences in the laterotrusive excursions and in the protrusion and retrusion movements between the patients and asymptomatic participants. The masticatory cycles of the 2 groups were similar.[9] By using a camera system, Ohashi et al[3] evaluated the angular symmetry of the condyle trajectory of the masticatory and border movements of the mandible in patients who underwent orthodontic surgery. Postoperatively, border laterality movements widened after the orthodontic surgery and border movement symmetries improved.[8] Patients with a skeletal class III have an asymmetric condylar range of motion on retrusion and an asymmetric Bennett angle. It has been reported that a month after orthognathic surgery in these patients, the maximum mouth opening range, laterotrusion range, angle, and the distance of the condylar movement were significantly reduced. The Bennett angle showed higher symmetry on both sides.[20]

These studies show the clinical importance of analyzing the symmetry of MM.[3,8-10,19,20] The currently available methods of evaluating MM involve the use of rulers, calipers, and visual analog scales.[2,23-25] These methods are straightforward and low cost, but their accuracy, standardization, and systematization can be uncertain. The ARCUSdigma (ARCUSdigma II facebow; KaVo) is a computerized axiograph that has been used to determine the condylar path inclination, Bennett angle, immediate side shift, and Bennett shift, allowing a qualitative on-screen analysis of MM.[26] This device is considered to be the gold standard for analyzing MM.[26-28] However, it interferes with the free MM because of the attachment of the facebow. Another commonly used device to evaluate MM is the mandibular kinesiograph, which also contains a facebow and has been criticized for inconsistent results.[29]

The earlier techniques analyzed only the symmetry of the superior contact border movements. In the present study, the symmetry of Posselt polygons was evaluated, and therefore, superior and opening border movements were analyzed.

The American Academy of Pediatric Dentistry reported that asymmetries in MM could be associated with TMDs.[4] It was stated that the quality and symmetry of MM should be recorded and analyzed.[8] Three-dimensional EMA systems allow the recording of movements with high spatial (0.3 mm) and temporal (sampling frequency of 1 kHz) precision. Therefore, a more complex analysis of the movements and their symmetries can be made.[3]

Limitations of the present study include that for the determination of the anatomic frontal, sagittal, and horizontal planes, the position of the participants with the head looking forward and the Frankfort plane parallel to the floor was used as a reference. Therefore, it is likely that the determination of the anatomic planes in each recording was not completely accurate, which is a possible source of error when obtaining the projections of the trajectories and the polygons in the different planes. The results obtained from this analysis on asymptomatic participants will be used as reference to conduct future studies on patients with different clinical conditions.

CONCLUSIONS

Based on the findings of this clinical study, the following conclusions were drawn:

1. The proposed technique allowed the assessment of the symmetry of mandibular movements in asymptomatic participants.
2. The evaluated parameters (mandibular trajectory, range, and area of polygons) maintained similar values on both left and right sides.
3. However, the polygons described by the mandibular border movements presented different morphology on each side.

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