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ORIGINAL ARTICLE

Displacement of the Mandibular Condyles Immediately after Herbst Appliance Insertion - 3D Assessment

Paula Loureiro Cheib[1], Lucia Helena Soares Cevidanes[2], Antonio Carlos de Oliveira Ruellas[3], Lorenzo Franchi[2,4], Wagner Fernando Moyses Braga[1], Dauro Oliveira[1], Bernardo Quiroga Souki[1]

[1]Department of Orthodontics, Pontifical Catholic University of Minas Gerais School of Dentistry, Bela Horizonte, Brazil
[2]Deparment of Orthodontics and Pediatric Dentistry, University of Michigan School of Dentistry, Ann Arbor, USA
[3]Department of Orthodontics and Pediatric Dentistry, Federal University of Rio de Janeiro School of Dentistry, Rio de Janeiro, Brazil
[4]Deparment of Orthodontics, University of Florence School of Dentistry, Florence, Italy

ABSTRACT

Objective: To test the following two hypotheses regarding the consequences of Herbst appliance (HA) insertion: 1) a significant clockwise mandibular rotation will occur and 2) the displacement of the condyles will follow the same magnitude of the changes of overjet (OJ) and overbite (OB).

Methods: Virtual 3D surface models of 25 patients were generated from cone-beam computed tomographs taken before treatment and immediately after HA insertion. Scans were registered on the cranial base and were analyzed using point-to-point measurements, color-coded maps, and semitransparent overlays. Statistical tests included correlation and simple regression analysis.

Results: Pitch rotation, ranging from −2.2° to 2.2° (mean, 0.2°), was observed in clockwise and counterclockwise directions. Condylar sagittal displacement presented a positive correlation with OJ changes. Each millimeter of OJ correction resulted in an anterior condylar displacement of approximately 0.95 mm. Vertical condylar displacement correlated with OB changes and varied mostly between 2 mm and 4.5 mm.

Conclusion: Immediately after HA insertion, no significant clockwise mandibular rotation was observed. The condyles were displaced anteriorly and inferiorly. Condylar anterior displacement and OJ correction presented a ratio close to 1:1. The vertical displacement of the condyles did not follow the same magnitude of OB changes.

Keywords: Herbst appliance, cone beam computed tomography, temporomandibular joint

INTRODUCTION

Following Herbst appliance (HA) insertion a new and transitory condyle-articular fossa relationship has been established within the temporomandibular joint (TMJ). While the literature has provided evidence about the dental and skeletal effects of the HA (1-5), little is known about the changes in the position of the mandibular condyles within the TMJ immediately after HA insertion (6-9). Important clinical questions remain unanswered regarding the insertion of the HA: a) How much do the condyles and mandible rotate after HA installation? b) How much do the condyles change their spatial position when several combinations of overbite (OB) and overjet (OJ) corrections are performed? c) Is there a correlation between OB and OJ correction and condylar displacement within the articular fossae? The literature suggests that after HA insertion, rotational and translational changes occur in the condyles and that such displacement triggers the bone remodeling process that occurs in both the articular fossae and the mandible during the therapeutic period (10,11).

The construction and overlay of virtual 3D surface models now allow for the precise evaluation of the real condylar displacement within the articular fossae rather than conventional measurements extracted from 2D radiographs (12). These quantitative and qualitative approaches allow the investigation of the correlation between condylar displacements and the amount of OB and OJ corrections.

The aim of this study was to determine the displacement of the mandibular condyles immediately after a one-step mandibular activation with HA using 3D imaging and superimposition techniques when several combina-

Corresponding Author: Dr. Bernardo Quiroga Souki, Department of Orthodontics, Pontifical Catholic University of Minas Gerais School of Dentistry, Bela Horizonte, Brazil E-mail: souki.bhe@terra.com.br

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tions of vertical and horizontal mandibular advancements were performed during a Class II correction. It was hypothesized that a clockwise mandibular rotation would occur and that a condylar displacement within the articular fossae would follow the same magnitude of OJ and OB reduction.

METHODS

The sample size was calculated based on data analysis of the first 10 consecutive cases retrieved from a university database. The following factors were considered: a) the primary research outcome (mandibular pitch), b) the clinical level of significant difference between T0 (baseline) and T1 (immediately after HA insertion) greater than 0.5° of the pitch, c) an alpha significance level of 0.05, and d) a beta of 0.2 to achieve a power of 80%. Thus, the sample in this retrospective observational study comprised 25 adolescents [12 males and 13 females, age: 12–16 years (mean=13.8±1.1 years)] with a dentoskeletal Class II malocclusion who had been treated with the HA at the Graduate Program in Orthodontics of the Pontifical Catholic University of Minas Gerais, Belo Horizonte, Brazil.

At T0, all patients presented a Class II malocclusion in the permanent dentition and an interincisal relationship that allowed a one-step mandibular activation to fully correct the Class II relationship. The amount of sagittal and vertical activation varied among the patients according to the amount of OB and OJ to be corrected with the one-step activation. The sex distribution of the patients according to OJ at T0 is shown in Table 1. All patients were treated during the pubertal growth period based on the cervical maturation method (13). Institutional Review Board approval for the study was obtained from the University of Pontifical Catholic University of Minas Gerais Ethics Committee. All patients' guardians signed an informed consent authorizing the use of orthodontic records for the purpose of this scientific investigation.

Cone-beam computed tomography (CBCT) scans were taken using an i-CAT machine (Imaging Sciences International; Hatfield, Pa) with a field of view of 16×22 cm and voxel of 0.3 0.3×0.3 mm. All patients were instructed to bite into the maximum occlusal contacts during scan capture. The analysis of serial CBCT images to evaluate changes between T0 and T1 included 3D analysis procedures using ITK-SNAP (open-source software; www.itksnap.org), SLICER (open-source software; www.slicer.org), Vectra Analysis Model software version 3.7.6 (Canfield Scientific Inc.; Fairfield, NJ), and ImageJ (open-source software; www.nih.gov). The 3D image analysis procedures included the following, approximation of T0 and T1 scans, construction of virtual 3D surface models of the cranial base, voxel-based image registration, and construction of virtual 3D models of the mandible, as previously described (14). Quantitative and qualitative measurements were performed according to the description mentioned below.

Quantitative assessments of positional changes between the 3D surface models of the mandible were performed using point-to-point landmark measurements and virtual analytics. Three landmarks were identified: the left condylar point (CoP), the right CoP, and the Menton point (MeP). CoP was defined as the mid-most superior aspect of the right and left condyles, while MeP was defined as the most inferior mid-sagittal point in the lower border of the Menton. As shown in Figure 1, changes in the Cartesian coordinates of CoP and MeP between T0 and T1 were used to assess the following: 3D condylar displacement (distance between CoP at T0 and at T1, measured bilaterally), 2D projected linear condylar displacement, and mandibular rotation. The posterior-anterior (PA) and inferior-superior (IS) 2D projected linear (ΔY and ΔZ, respectively) displacements of CoP from T0 to T1 were measured in the sagittal plane (YZ), as shown in Figure 2a. The left-right (LR) 2D projected linear (ΔX) displacement, shown in Figure 2b, was measured in the axial plane (XY). As shown in Figure 2c, the mandibular rotation was measured as pitch, roll, and yaw (15). Mandibular pitch was measured as angular changes between the lines through the right CoP and MeP at T0 and T1 in the sagittal perspective view. Roll was measured as angular changes between the lines through the right and left CoP at T0 and T1 in the coronal perspective view. Yaw was measured as angular changes between the lines through the right and left CoP at T0 and T1 in the axial perspective view. Positive values indi-

Table 1. Sex distribution of 25 patients according to overjet at T0 (measured in mm)

OJ	Male	Female
2.0-4.0	1	2
4.1-7.0	3	5
7.1-9.0	6	4
9.1-11.6	2	2
Total	12	13

OJ: overjet

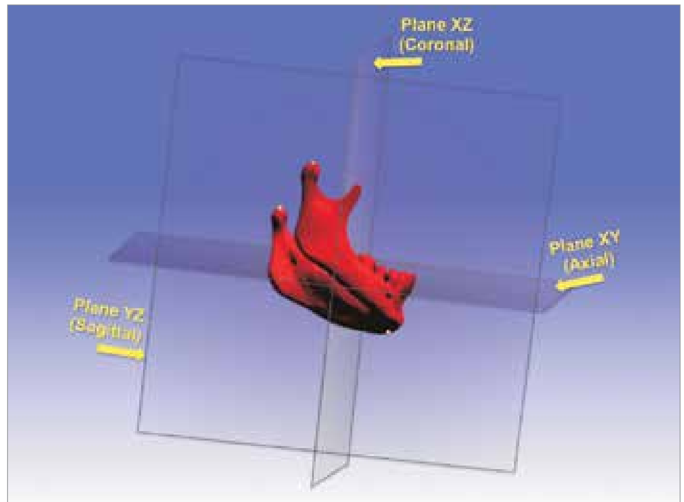

Figure 1. T0 and T1 surface models of the mandible were located in a common coordinate system determined by the registration relative to the cranial base (Plane XY: Axial; Plane YZ: Sagittal; Plane XZ: Coronal). The condylar landmark was referred to as CoP and was located in the mid-most superior aspect of the right and left condyles. The most inferior mid-sagittal point in the lower border of the Menton was referred to as MeP. Only the T0 model is shown here.
CoP: condylar point; MeP: Menton point

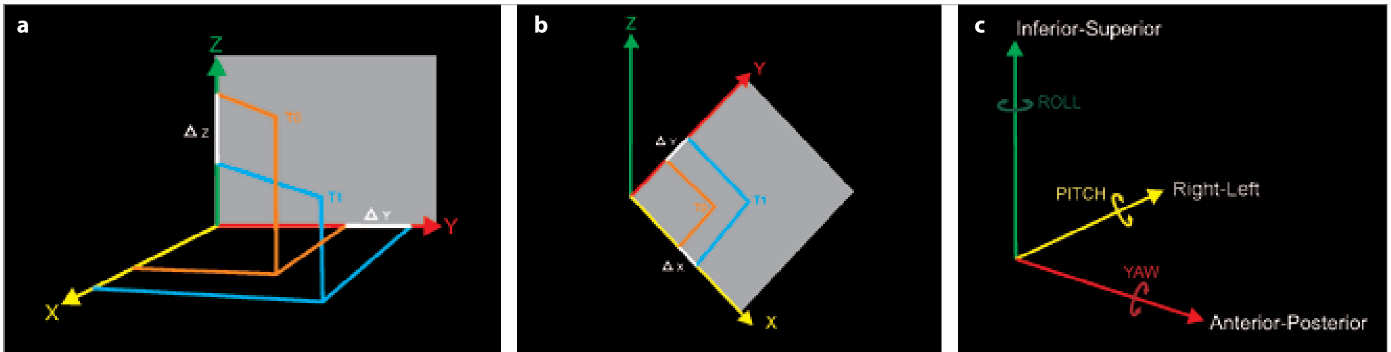

Figure 2. a-c. 2D projected condylar displacement. Sagittal plane (YZ): ΔZ (inferior-superior) and ΔY (posterior-anterior) linear displacements (a). Axial plane (XY): ΔX (right-left) displacement (b). Mandibular rotational displacements around the X, Y, and Z axes (c).

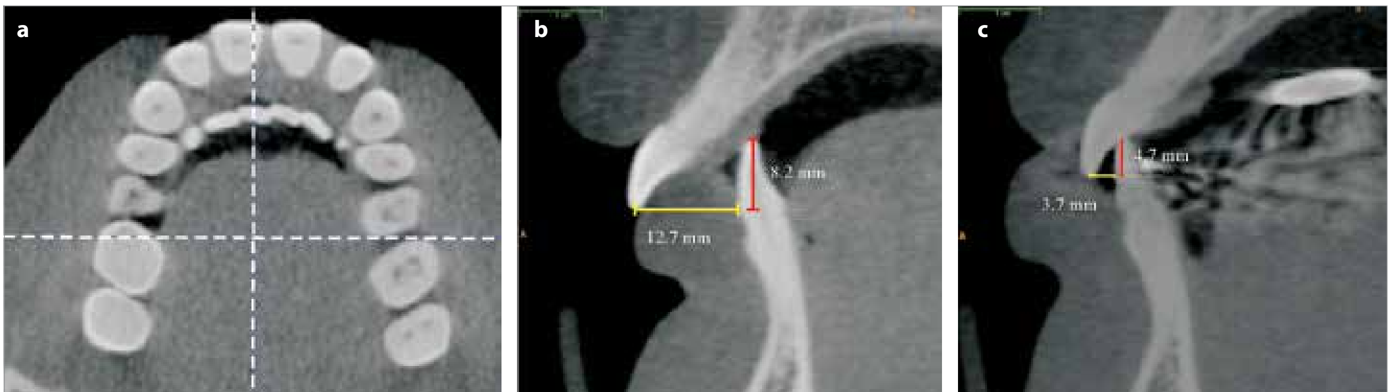

Figure 3. a-c. Measurement of overjet and overbite. In the axial view, including the maxillary and mandibular incisors, the sagittal cut was defined in the mid-point of the incisal border of the right mandibular central incisor (a), T0 scan (b), and T1 scan (c).

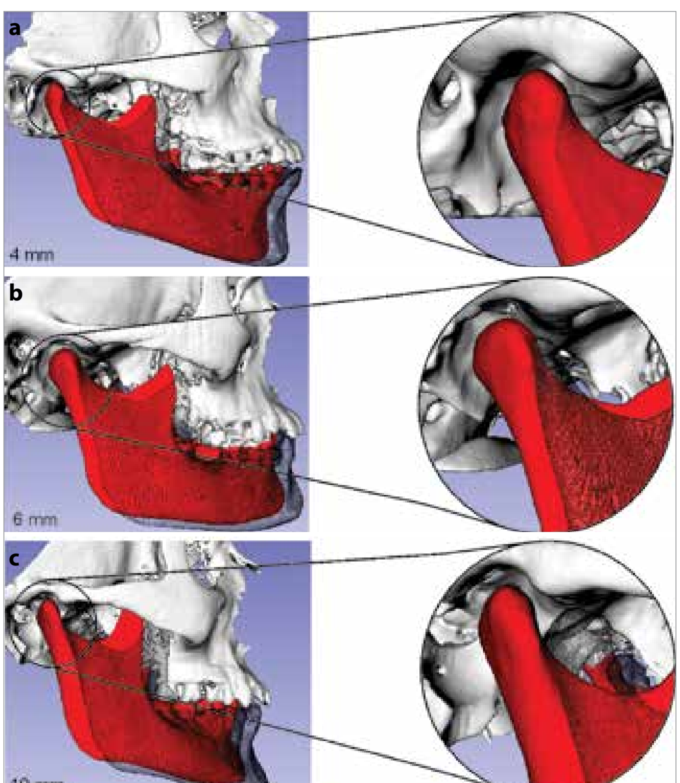

Figure 4. a-c. Semitransparent overlays of T0 and T1 virtual models. Four millimeters of mandibular advancement (a), 6 mm of mandibular advancement (b), and 10 mm of mandibular advancement (c).

cated rightward yaw/roll rotations and clockwise pitch rotation, while negative values indicated leftward yaw/roll and counter-clockwise pitch rotations. OB and OJ were measured with ImageJ software using the right permanent central incisors, as shown in Figure 3. OJ was defined as the distance between the incisal border of the maxillary central incisor and the buccal surface of the mandibular central incisor along a projected orthogonal line parallel to the occlusal plane. OB was measured from the incisal border of the mandibular central incisor to the projected orthogonal line of the maxillary central incisor.

Interactive visual analytics included graphic displays with qualitative assessments using semitransparent overlays of the 3D models at T0 and T1 and quantitative assessments of the condylar and chin surface displacements, as shown in Figure 4. All visual analytic assessments were performed using the SLICER software.

Data analysis was performed with Statistical Package for the Social Sciences version 21.0 (IBM Corp.; Armonk, NY, USA). To determine errors in landmark identification and virtual models measurements, 25 scans from a total of 50 scans in the current study were randomly selected, and the models were then re-built and re-measured by two investigators after a two-week interval. Random error was measured according to Dahlberg's formula (16), and intra- and inter-observer agreement measurements were tested using intra-class correlation coefficients (ICC) with a confidence level of 95%. The systematic error (bias) was

Table 2. Descriptive data according to overjet and overbite at T0 and T1, incisor displacement, 3D condylar displacement, 2D projected condylar displacement, and mandibular rotation from T0 to T1 in the 25 patients

Measurement	Mean	SD	Minimum	Maximum
Overjet and Overbite (mm)				
Overjet T0	6.7	2.9	4.0	12.7
Overjet T1	1.9	1.2	0	4.2
Overbite T0	3.6	2.0	1	8.2
Overbite T1	2.0	1.4	0	5.8
Incisor displacement (mm)				
Overjet change	4.8	2.6	2.0	11.6
Overbite change	1.6	1.7	0.3	4.0
3D condylar displacement (mm)				
Right	5.2	2.4	1.8	11.1
Left	5.5	2.7	1.9	11.6
2D projected condylar displacement (mm)				
IS right	3.5	1.2	1.2	5.0
IS left	3.5	1.1	1.3	5.0
PA right	4.8	2.5	1.6	10.3
PA left	4.9	2.7	1.5	11.1
LR right	0.5	0.5	0.0	2.0
LR left	0.5	0.4	0.0	1.5
Mandibular rotation (°)				
Roll	0.1	0.4	-0.8	1.0
Yaw	-0.1	0.7	-1.2	1.3
Pitch	0.2	1.1	-2.2	2.2

IS: inferior - superior; PA: posterior - anterior; LR: left – right; SD: standard deviation
Negative (-) values indicate leftward roll/yaw, or counterclockwise pitch rotation
Positive (+) values indicate rightward roll/yaw, or clockwise pitch rotation

assessed using the paired t-test. All variables showed normal distribution (Kolmogorov-Smirnov), and the level of significance was set at 0.05. Pearson's correlation coefficients were calculated to assess the association of OJ and OB changes with condylar displacement as well as the total mandibular rotation. Simple linear regression models were used to describe the dependence of condylar displacement with OJ changes immediately after HA installation.

RESULTS

The ICC showed high agreements (>0.90) between both intra and inter-observers. There were no statistically significant systematic errors between the two measurements performed by the same operator (p>0.05). For random error values, they varied between 5.3 and 10.1%, which was considered not clinically significant. The HA activation resulted in OJ changes ranging from 2 to 11.6 mm and OB changes ranging from 0.3 to 4 mm (Table 2). Table 2 summarizes the descriptive data according to incisors displacement, 3D condylar displacement, 2D projected condylar linear displacement, and mandibular rotation from T0 to T1 in the 25 patients following HA insertion. Table 3 presents the Pearson correlation coefficients between OJ and OB changes and the modifications in the condylar position. Figure 5 shows the linear regression analysis for the 3D condylar displacement, PA condylar displacement, and IS condylar displacement based on OJ changes. Figure 4a-c present semitransparent overlays of the condylar spatial changes following HA insertion. The changes in the condyles position immediately after HA installation can be summarized as follows:

Table 3. Pearson coefficient correlation between overjet and overbite, 3D condylar displacement, 2D projected condylar displacement, and mandibular rotation

	OJ (mm)	OB (mm)
3D condylar displacement (mm)		
Right	0.850***	0.518*
Left	0.898***	0.507*
2D projected condylar displacement (mm)		
IS right	0.532**	0.565**
IS left	0.626**	0.541**
PA right	0.866***	-0.392
PA left	0.890***	-0.312
LR right	0.122	0.330
LR left	0.008	0.178
Mandibular rotation (°)		
Roll	-0.252	-0.082
Yaw	0.027	0.038
Pitch	-0.151	0.126

OJ: overjet; OB: overbite; IS: inferior-superior; PA: posterior-anterior; LR: left-right
*p<0.05; **p<0.01; ***p<0.001

The mandibular pitch rotation following HA insertion was observed both in clockwise and counterclockwise directions and was not significantly correlated to the amount of OJ and OB correction: As shown in Table 2, the mandibular rotational changes in pitch ranged from -2.2° to 2.2°. Fourteen patients presented clockwise rotation while 11 showed counterclockwise rotation. Even though the mean pitch rotation was 0.2°, the modulus of pitch was greater than 0.5° in 19 subjects (11 in clockwise rotation) and greater than 1° in 10 subjects (6 in clockwise rotation). As shown in Table 3, weak correlation coefficients were found between OJ and OB changes and mandibular pitch rotation.

The mandibular roll and yaw rotations following HA were small and not significantly correlated to the amount of OJ and OB correction: The mandibular rotational changes in roll and yaw were small. As shown in Table 2, mandibular roll ranged from -0.8° to 1.0° and yaw ranged from -1.2° to 1.3°. Twenty-four subjects presented a mandibular roll rotation between -0.5° and 0.5°. A yaw rotation between -0.6° and 0.6° was measured in 21 patients. As shown in Table 3, weak correlation coefficients were found between OJ and OB changes and mandibular roll and pitch rotation.

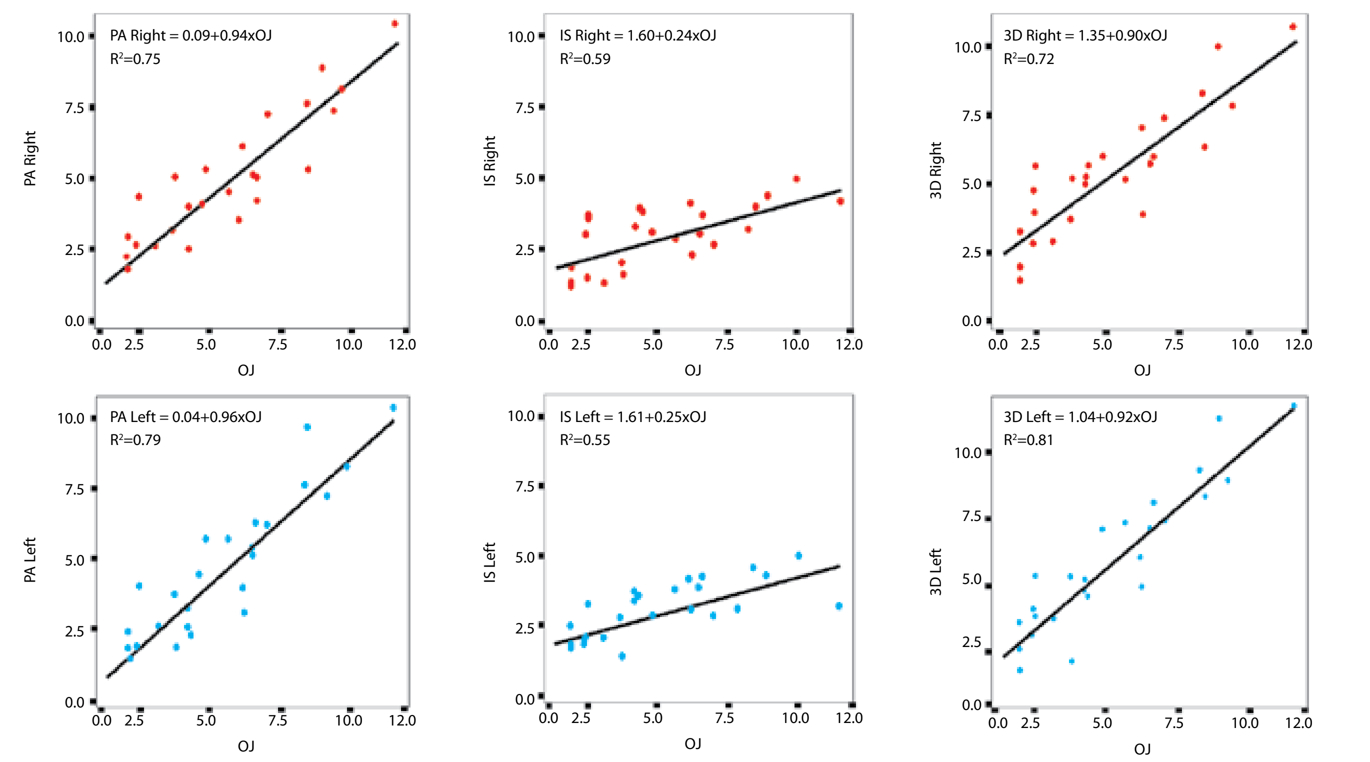

Figure 5. Linear regression analysis of OJ changes and condylar displacement (PA, IS, and 3D): scatter plots, regression lines, equations, and coefficient of determination (R^2).
OJ: overjet; PA: posterior-anterior; IS: inferior-superior

Following HA insertion, the right and left condyles displaced similarly in the three planes of space: Condyles moved approximately 4.8 mm anteriorly (4.8±2.5 mm on the right side vs. 4.9±2.7 mm on the left side) and approximately 3.5 mm inferiorly (3.5±1.2 mm on the right side vs. 3.5±1.1 on the left side). No predominant right or left condyle displacement was observed and no statistically significant differences (p>0.05) between right and left condyles were detected (0.5±0.5 mm on the right side and 0.5±0.4 mm on the left side).

The 3D and 2D condylar displacements within the mandibular fossae were significantly correlated with OJ and OB changes: Table 3 shows that very strong positive correlations (p<0.001) were observed between OJ reductions and the 3D condylar and 2D projected PA displacements. OJ and OB changes presented strong positive correlations (p<0.01) with the 2D projected IS displacement. The amount of OB change presented a moderate positive correlation (p<0.05) with the 3D condylar displacement and a weak (p>0.05) and non-significant negative correlation with the 2D condylar PA displacement. Similarly, a weak (p>0.05) and non-significant correlation was also found between OJ and OB changes after HA insertion and the left-right 2D condylar linear displacement. Scatter plots with regression lines and equations of the significant correlations of OJ are shown in Figure 5. Each 1 mm of OJ correction produced 0.94 to 0.96 mm of PA condylar movement. As shown in Table 2, the mean condylar IS displacement was 3.5 mm (1.2 to 5.0 mm). Most patients (n=20) showed an IS condylar displacement ranging from 2 to 4.5 mm, despite OJ correction. Figure 4a-c illustrate the variability of the amount of condylar displacement within the mandibular fossa that took place with different amounts of HA activations for three patients (4 mm, 6 mm, and 10 mm, respectively).

DISCUSSION

The present study assessed, for the first time, the 3D changes in the position of the mandibular condyles immediately after HA insertion and shed some light into the variability of condylar displacements related to different anterior mandibular repositioning with the HA. This study used 3D virtual modeling and the voxel-based superimposition technique (14) to elucidate condylar displacements within the articular fossa. Over the past decades, investigations on the HA have been performed with 2D radiographic images (2,6,17), cross-sectional multiplanar magnetic resonance imaging (MRI) images (6-9), and histologic examinations (18). Due to the limitations of these methods, condylar changes immediately after HA installation have not been fully understood. The point-to-point landmark measurements and 3D semitransparent overlays used in this study clearly showed that the condyles were repositioned anterior to the edge of the articular eminence after HA installation, which was expected (6,8).

The development of this retrospective study was only possible because of the availability of a CBCT database of patients who had used HA, and whose records included a scan taken immediately after HA insertion due to legal reasons. In Brazil, if enrolled in litigation, health care providers are required to present complete patients' records. Thus, clinicians are recommended to include all images that can prove that no iatrogenic effects were generated during orthodontic therapy. Therefore, during a four-year period, CBCT images were collected to record possible changes in the condyles position associated with HA treatment. Since no evidence of TMJ problems immediately after HA insertion were found, the acquisition of this CBCT's was discontinued. The period between T0 and T1 (immediately after HA insertion) varied between three to five weeks. The use of 3D virtual models to investigate this issue, using CBCT scans of patients obtained shortly after HA installation, allowed more accurate measurements. Indirect techniques used to evaluate mandibular biomechanics have had limited success due to their ability to evaluate only hard tissues (19). Laboratory assays that have been progressively used by researchers on the TMJ cannot reproduce the actual biological settings such as the inclination of the mandibular fossa, the sagittal condylar inclination, the muscle restrain properties, and the morphology and viscoelastic properties of the articular discs. However, the current study methodology is laborious, and the construction of the 3D models is time consuming.

In the present study, OJ changes showed a strong positive correlation with 3D condylar displacement. OJ reduction, which is one of the goals of any Class II treatment, is strongly correlated with the amount of 3D condylar displacement and with the 2D PA linear displacement of the condyles. However, in some patients, due to a small counterclockwise mandibular rotation (<2.2°), pogonion advancement was even greater than OJ changes. Moreover, OJ reduction was moderately correlated to IS condylar displacement within the articular fossae. The correlation coefficients shown in Table 3 and the regression equations presented in Figure 5 show that OJ correction presented a very strong correlation ($r>0.866$; $p<0.001$) with PA condylar displacement. Each millimeter of OJ correction would cause approximately 0.94–0.96 mm of PA condylar displacement. This small difference between the amount of condylar PA displacement and OJ correction may be explained by the pitch rotation of the condyle within the fossa. Despite the fact that the mean pitch rotation was only 0.2°, most of the patients (n=19) showed a modulus of pitch of greater than 0.5° and 10 patients had a modulus of pitch greater than 1°.

The anterior-posterior maxillo-mandibular discrepancy in Class II malocclusions often enhances the overeruption of the incisors. Thus, increased OB is a common finding in Class II patients, which often limits the amount of space available for AP mandibular advancement with HA. In the current study, OB changes after HA insertion presented a strong positive correlation ($r>0.541$; $p<0.01$) with vertical condylar displacement (IS) and a moderate correlation ($r>0.507$; $p<0.05$) with 3D condylar displacement. The weak non-significant negative correlation between OB and the registered horizontal condylar displacement ($r>0.312$; $p>0.05$) indicates that OB correction does not affect the mandibular sagittal gain. However, there is a tendency toward anterior-inferior facial height increase after HA insertion due to IS condylar displacement. With OB correction, the bite opens and a posterior disocclusion is established. Previous studies have suggested that a deep bite is corrected in patients with HA insertion due to molar and premolar extrusion (20), while the vertically displaced condyles "remodel" into the articular fossae (18). One of the concerns and criticisms regarding HA treatment is the lack of vertical control, which may be a major problem in hyperdivergent subjects (21-23). Worsening in the vertical dimension of Class II patients (23) is often associated with two aspects: mandibular clockwise rotation and the vertical displacement of the condyles within the articular fossae. With regard to mandibular rotation, this study has shown that clockwise pitch is small, at least immediately after HA insertion. Interestingly, several patients (n=11) even showed a counterclockwise rotation immediately after HA insertion, as illustrated in Figure 4, and no correlation between mandibular pitch and OB changes was observed. In the graphic visualization using semitransparent overlays, it is clear that the changes in mandibular pitch were small, even in hyperdivergent individuals (Figure 4a). With regard to the vertical displacement of the condyles, the present findings revealed that despite the sagittal one-step HA activation, the immediate downward condylar displacement was 2.7 mm on average. The articular eminence height may be the major determinant of vertical condylar displacement in the present study.

The results of this preliminary investigation do not allow inferences about whether smaller increments of mandibular activation using a stepwise protocol or a small one-step correction of a mild maxillo-mandibular discrepancy would lead to a greater skeletal response with regard to condyle/fossae remodeling, as suggested by a previous report (24). However, it may be suggested that despite not exactly being in a 1:1 ratio, a significant OJ correction with HA is associated with a considerable condylar displacement and probably with a significantly high tension and compression of TMJ tissues. Moreover, based on previous data about the translational and rotational movements of the mandible during mouth opening and closing, it was expected that even with small mandibular HA activations, a relatively greater rotation of the condyle along its axis would be more likely to occur than during condylar translation (25). However, these findings showed that the overall mandibular rotation following HA insertion was very small, regardless of the amount of OB and OJ correction. Therefore, the TMJ kinematic behavior immediately after HA insertion is different than the usual opening and closing movements of the mandible. It is still unknown whether the amount of rotation or translation of the condyles within the fossa influences the bone remodeling process and the treatment stability. It would be beneficial for additional studies to investigate this.

CONCLUSION

The following conclusions can be made about HA insertion:

1. Clockwise and counterclockwise mandibular pitch rotations and mandibular roll and yaw rotations were small and not positively correlated to OB and OJ changes.
2. No significant differences between right and left condylar displacements were observed.
3. The 2D and 3D sagittal and vertical condylar displacements within the mandibular fossae were positively correlated with OJ changes.

4. Condylar vertical displacement was correlated to OB changes, but not in the same magnitude.

Ethics Committee Approval: Ethics committee approval for this study was received from the institutional review board of Pontifical Catholic University of Minas Gerais (Approval number: 21534013.8.5137).

Informed Consent: Since this study was done using the university database collected before the study design, written/verbal information for consent was not included.

Peer-review: Externally peer-reviewed.

Author contributions: Concept - L.H.S.C., A.C.O.R., L.F., D.D.O., B.Q.S.; Design - L.H.S.C., A.C.O.R., L.F., B.Q.S., Supervision - B.Q.S., A.C.O.R.; Resource - L.H.S.C., D.D.O.; Materials - P.L.C., L.H.S.C., W.F.M.B.; Data Collection and/or Processing - P.L.C., W.F.M.B., B.Q.S.; Analysis and/or Interpretation - P.L.C.V., L.H.S.C., A.C.O.R., L.F., B.Q.S.; Literature Search - P.L.C., W.F.M.B.; Writing - P.L.C., L.H.S.C., A.C.O.R., D.D.O., B.Q.S.; Critical Reviews - L.H.S.C., A.C.O.R., L.F., D.D.O., B.Q.S.

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