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Original Article

# Mandibular movement analisys by means of a kinematic model applied to the design of oral appliances for the treatment of obstructive sleep apnea

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A B S T R A C T

*Background:* Mandibular advancement devices (MADs) are one of the treatment options used for the obstructive sleep apnea syndrome (OSAS). At present, MADs are designed with standard titration systems, without considering each patient's anatomical characteristics of the temporomandibular joint and mandible shape. The main objective of this study is to evaluate if a variability in mandibular morphology will influence the displacement of the jaw with a MAD. Such knowledge will be of help to find optimal mandibular positions with MAD even when opening the mouth.
*Methods:* By using a mandibular movement model, the movement patterns of different points on the chin have been analyzed. The influence of different skeletal mandibular shapes on these movements have also been studied. The results show differences in the movement patterns of the lower front teeth depending on its distance to the center of the condyle, with a more horizontal direction in those in which there is a greater distance.
*Results:* Variations in mandibular morphology imply differences in movement patterns of the analyzed points of the mandible. Consequently, MADs should be designed according to each patient's anatomy to avoid mandibular retrusion in those areas that may narrow the upper airways.
*Conclusions:* This study may help to understand why not all patients move their lower jaws forwards equally with the same degree of mandibular protrusion measured in relation to the teeth. These results might also partially explain why airway obstruction is more severe in certain untreated sleep apnea subjects than in others when opening their mouth during sleep.


## 1. Introduction

The most important alternative to Continuous Positive Air Pressure (CPAP) for the treatment of the Obstructive Sleep Apnea Syndrome (OSAS) are Mandibular Advancement Devices (MADs) [1]. MADs force a mandible protrusive positioning in order to widen the airway space [2–4]. These devices can be made of one or two pieces, one that fits in the upper dental arch and another in the lower one. These 2-piece MADs can regulate the degree of mandibular advancement and allow other movements such as lateral displacement and opening [5,6].

MADs are set in an initial position with a certain protrusion and opening level (Starting Position, SP). The most commonly used values for the SP are an initial protrusion between 50% and 75% of the maximum mandibular advancement and an interincisal opening between 2 and 8 mm although there are studies with an interincisal opening of between 4 and 14 mm [7].

The mandibular displacements that can modify the caliber of the upper airway are due to anteroposterior and superoinferior movements [8,9]. These displacements can be studied by tracing the movements of a certain point on the mandible, such as the tip of the lower central incisors. These movements follow a common pattern (Posselt's diagram), with individual variations [10].

One of the most important points within the structure of the jaw is the chin, particularly its posterior part, where the main lingual muscles are attached to the mandible (apophysis geni). The

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genioglossus muscle is the most important one of these muscles, since it constitutes the largest volume of the tongue and is its largest protrusive muscle [11]. Therefore, it seems important to know the movements that a MAD will produce in the area of the apophysis geni, since it might be a way to evaluate its effect on this muscle.

There are studies that show that certain mandibular morphologies (retrognathia, dolichofacial growth pattern) predispose to OSAS [12]. Other studies find associations between mandibular morphology and the probability of positive response to treatment with MADs [13,14]. However, there is a lack of studies on mandibular kinematics to explain the reason for these findings. Multiple studies record mandibular movement [15–19] and predict mandibular kinematics [20–24]. However, to our knowledge, this is the first work to analyse the differences between subjects.

The mandible moves with a range of movement that depends on the temporomandibular joint [25] and are controlled and limited by the ligaments, the articular capsule and the muscles [26]. When opening the mouth, the mandible rotates posteriorly and the mandibular symphysis retrudes [27]. The normal mandibular opening in healthy adult subjects while sleeping is up to 5 mm during 90% of the time. This is known as physiologic rest position of the mandible or freeway space [28–30]. Several studies show that patients with OSAS open their mouth more than 5 mm during most of their sleeping time [29,31,32], reaching apertures of over 15 mm [33]. The decrease in muscle tone of the masticatory and lingual muscles during sleep added to the jaw weight, particularly in the supine position, lead to opening of the mouth and the dorsal displacement of the jaw and tongue. As a consequence, there is a pharyngeal narrowing that increases the air resistant of the upper airways that finally leads to obstructive apnea [34]. A mouth opening of more than 5 mm results in a significant reduction in the retropalate and retrolingual area as well as a reduction in the distance from the hyoid to the jaw and a more posterior position of the jaw [8]. Controlling the opening with a MAD increases the effectiveness of the treatment by preventing post-rotation and subsequent collapse of the airway [35–43].

At present, existing MADs cause changes in mandibular position without considering the different morphologies of patients' upper airway or jaw. It would be desirable to reach a level of personalization based on each person's anatomical variations and to have models that could predict the position of each patient's lower jaw as well as its effect on the airway.

The present study proposes the use of a kinematic model of mandibular movement in the sagittal plane to study how mandibular morphology affects the displacements of different parts of the mandible, their variations and the pattern they follow. A secondary focus of this work is set on finding predictive formulas for these displacements, since this could be useful to predict which movements will be induced in each individual by a MAD.

## 2. Material and methods

Fifty-two Dentistry students at the Alfonso X University in Madrid, aged 19 to 23 (mean age 21.3 SD 1.7; 29 females and 23 males) agreed to participate in this study. They were chosen randomly, voluntarily, with no economic compensation for their participation. None had had either temporomandibular joint symptoms or maxillofacial surgery done. This study was approved by the ethical review board of the Alfonso X University in Madrid (UAX-2016-021).

All subjects had their maximum anterior and posterior mandibular movements measured using a George gauge (GG) with a 5-mm fork [27]. The GG is an instrument that allows measuring the anteroposterior movements of the lower incisor tips with respect to the upper ones. The origin coincides with the edge-to-edge position of the incisors when their outer edges are aligned in contact with the George gauge. Positive movements are those when the lower front teeth are situated in front of the upper ones and negative movements are those when the lower front teeth are behind the upper ones. Maximum mouth opening was measured from the tips of the superior and inferior incisors, using a conventional ruler.

Each subject had a lateral cephalometric x-ray taken. The images were scaled with the help of a mm ruler included in the x-ray. The position of the mandible when the x-rays were performed did not affect the procedure, as they were used to measure fixed values such as points on the articular fossa shape or distances from the landmarks to the center of the condyle.

Some points on the mandible were identified and distances between them were measured using an image analysis software tool (Fig. 1). The position of several points on the articular fossa were measured to predict the movement of the mandible. Other selected landmarks were the following:

- Point Cn: center of the condyle representing the center of rotation of the mandible.
- Point In: lower incisor tip which is the reference point commonly used to quantify forward movement of the mandible produced by a MAD.
- Point Ge: its position roughly corresponds to the apophysis geni where the genioglossus muscle is inserted.
- Point Go: gonion, the most posterior-inferior point of the mandibular body contour.

For each selected landmark, x and y coordinates were measured. The origin of the X–Y coordinate system was set according to the GG criteria, considering the X-axis going through the tip of the upper incisor and parallel to the maxillary occlusal plane and the Y-axis as a perpendicular line tangent to the upper incisor (Fig. 1). Based on the x and y coordinates of these landmarks, the following values were calculated (see Fig. 2a and b):

- Mandibular Length to the lower front teeth (MLin): distance between the center of the condyle and the lower incisor tip.

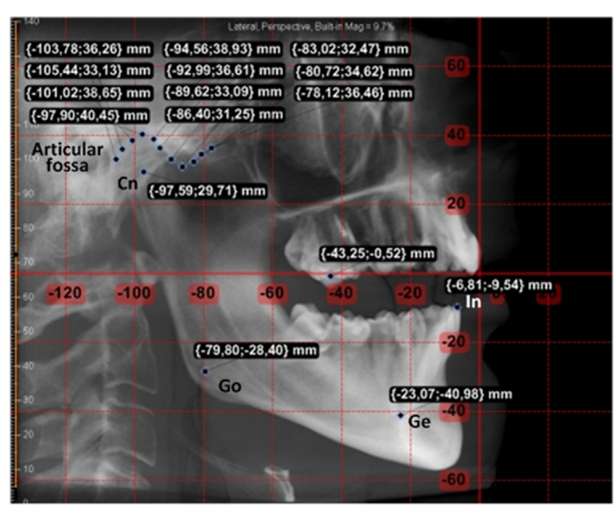
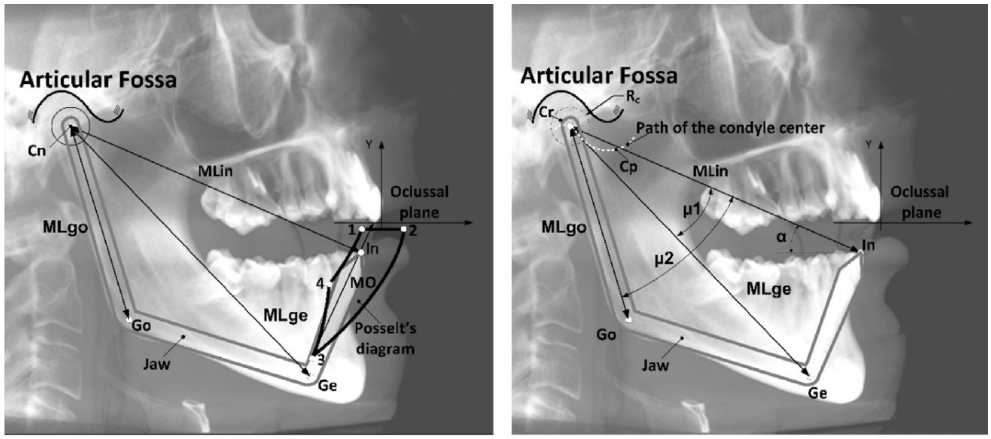



**Fig. 1.** Lateral cephalometric x-ray with the mm ruler on the left, the X–Y axes drawn in red bold lines and the x,y coordinates of the selected points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)




a) b)

**Fig. 2.** (a) Lateral cephalometric x-ray with a kinematic scheme of the mechanism that reproduces mandibular movement in the sagittal plane. (b) Parameters to calculate the borders of the movement diagrams of the selected points (lower incisor, apophysis geni and gonion).

- Mandibular Length to the apophysis geni (MLge): distance between the condyle and point Ge.
- Mandibular Length to the gonion (MLgo): distance between the condyle and point Go.
- Angle between the occlusal plane and MLin ($\alpha$).
- Angle between MLin and MLge ($\mu_1$).
- Angle between MLin and MLgo ($\mu_2$).
- The position and equation of the curve defined by the glenoid fossa.

This set of parameters allows finding the range of movements for the lower incisor, apophysis geni and gonion. If these parameters are obtained for any subject, an algorithm can be used to calculate the border movements of the aforementioned points, beyond which they cannot move any further in the sagittal plane. This way, the differences in mandibular movement for different morphological types can be evaluated. It is important to comment that when using a MAD, the mandible has one degree of freedom in the sagittal plane and another one for laterality. In this paper, we focus on the movement in the sagittal plane. Therefore, when opening the mouth, any point on the mandible can move only along a predefined path, no matter if the patient is asleep or awake.

### 2.1. Kinematic model of the mandible

Posselt's diagram is generated by the set of movements that the lower front teeth can perform in the sagittal plane [44]. These movements are a consequence of a translation along the glenoid fossa of the axis that passes through the two condyles and a rotation of the mandible about this axis.

The equations that represent each border of Posselt's diagram have been calculated by Bataller et al. [24], in their mandibular kinematic model. This algorithm can be applied to find the position of any other point of the jaw, such as the apophysis geni and gonion. To do so, we need to know the distance between the condyle center and these points, *MLge* and *MLgo*, respectively (Fig. 2a). In addition, we need to know angles $\mu_1$ and $\mu_2$ of *MLge* and *MLgo* with respect to *MLin* (Fig. 2b). These values can be measured on a lateral x-ray.

Fig. 2a shows the proposed model assuming that the lower incisor moves in the sagittal plane. The aforementioned parameters are displayed on a lateral x-ray (either side can be used). This model, which has two degrees of freedom, a mandibular rotation and the translation of the condyle along the curve of the glenoid fossa, allows generating borders 1, 2, 3 and 4 of the lower front teeth movement as follows:

- Points 1 and 2 represent the position of maximum retrusion and protrusion respectively, so that straight border 1–2 shows forward movement of the lower incisor. This movement can be measured with a George gauge with forks of different thicknesses avoiding dental contact as shown in Fig. 2a. The fork thickness has to be indicated in the algorithm to calculate the

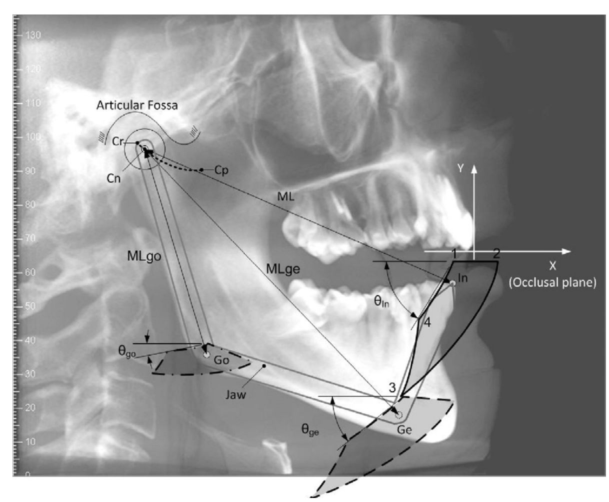



**Fig. 3.** Border movement diagram for the incisor (continuous line), for the apophysis geni (dashed line), for the gonion (dashed-dotted line) and for the condyle (dotted line).

**Table 1**
Mean position of the lower incisor tip, apophysis geni and gonion with respect to the condyle, measured in millimeters on lateral x-rays of the 52 subjects studied.

| Variables | Lower incisors | | Apophysis Geni | | Gonion | | Overbite | |
|---|---|---|---|---|---|---|---|---|
| | x | y | x | y | x | y | x | y |
| Mean | 90.68 | −47.95 | 69.90 | −79.11 | 4.51 | −56.37 | 3.54 | −1.93 |
| SD | 7.62 | 7.09 | 8.69 | 10.37 | 4.90 | 9.53 | 1.06 | 1.91 |

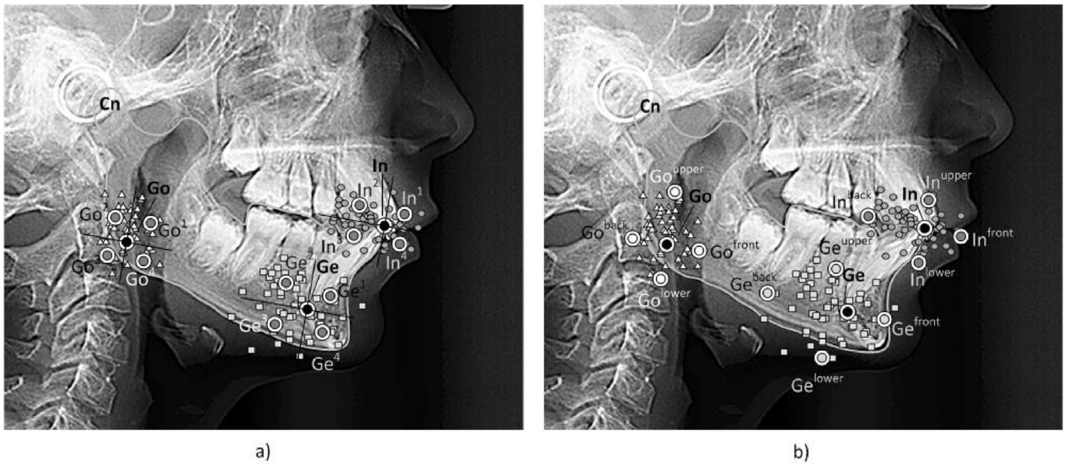



**Fig. 4.** X-ray of a patient whose values are close to the mean values (black dots). The position of the gonion, apophysis geni and lower incisor is represented with triangles, squares and circles respectively for the 52 subjects studied. The analysed points are represented with a circle with a white border. (a) Mean points in the four quadrants defined for the incisor, apophysis geni and gonion and (b) Points on the extreme upper, lower, front and back positions for the incisor, apophysis geni and gonion.

**Table 2**
Mean values of protrusion, retrusion and interincisal opening in millimeters of the aforementioned 52 subjects. The table shows the x-y coordinates of the lower incisor tip.

| Variables | Maximum retrusion | | Maximum protrusion | | Maximum interincisal opening |
|---|---|---|---|---|---|
| | x | y | x | y | |
| Mean | −5.5 | −5 | 6.8 | −5 | 53 |
| SD | 1.3 | – | 1.5 | – | 7 |

**Table 3**
Mean values of angle $\theta_{In}$, x and y distances between the condyle and lower incisor tip of the aforementioned 52 subjects grouped by quadrants.

| Quadrant | Incisor | | | | | |
|---|---|---|---|---|---|---|
| | $\theta_{In}$ (°) | SD | X (mm) | SD | Y (mm) | SD |
| 1 | 65.69 | 4.80 | 96.94 | 4.53 | −43.78 | 4.10 |
| 2 | 64.10 | 2.66 | 84.29 | 4.26 | −42.33 | 4.05 |
| 3 | 63.01 | 2.23 | 83.80 | 3.90 | −53.35 | 5.30 |
| 4 | 63.95 | 3.52 | 96.96 | 3.92 | −54.47 | 4.34 |

**Table 4**
Values of angle $\theta_{In}$, x and y distances between the condyle and the lower incisor tip of the four mandibles with extreme vertical and horizontal positions of the lower incisor among the 52 subjects studied.

| Extreme position | Incisor | | |
|---|---|---|---|
| | $\theta_{In}$ (°) | X (mm) | Y (mm) |
| Upper | 66.78 | 90.83 | −40.39 |
| Lower | 60.96 | 93.36 | −60.42 |
| Front | 66.61 | 99.33 | −48.89 |
| Back | 63.42 | 77.80 | −47.68 |

border correctly. Once points 1 and 2 have been found, the extreme positions of the center of the condyle can be calculated, points $C_p$ and $C_r$ in Fig. 2b.

- When opening the mouth maintaining maximum protrusion, section 2-3 is obtained. Point 3 is the position of the lower incisor for maximum mouth opening. Section 2-3 can be traced as an arc of a circle with radius MLin and center $C_p$ (Fig. 2a).
- When closing the mouth, forcing the mandible to move backward, section 3-4-1 is obtained. Sub-section 3-4 can be drawn with an arc calculated from a translational movement and linear rotation. Point 4 is at a distance of 22.5 mm [10] from point 1. Finally, the jaw performs a pure rotation and section 4-1 can be traced as an arc of a circle with radius MLin and its center at point $C_r$.

All the studied landmarks belong to the same body, the jaw. Therefore, all of them follow the same pattern of movements and are governed by the same equations. However, the borders of their movement diagrams will be different depending on their position relative to the center of the condyle.

Applying the previously explained algorithm to a subject, the curves represented in Fig. 3 are reproduced. The method allows obtaining the curves for any patient as long as the needed parameters have previously been obtained. Angles μ1 and μ2 and distances MLge and MLgo will be needed to obtain the movement diagram of the apophysis geni and Gonion.

In order to compare the angular position of Posselt's diagram in different patients, a straight line from point 1 to point 4 has been defined (Fig. 3). Then, the angle between this line and the oclusal plane has been measured in each x-ray for the incisor, apophysis geni and gonion diagrams, obtaining angles $\theta_{In}$, $\theta_{Ge}$ and $\theta_{Go}$ respectively.

## 3. Results

The aforementioned mathematical model was applied to 52 subjects. To do so, we have obtained the x and y coordinates of the lower front teeth, apophysis geni and gonion with respect to the centre of the condyle. The mean of the obtained values is listed in Table 1. Fig. 4a and b shows a subject's x-ray with the positions of the incisor (In), apophysis geni (Ge) and gonion (Go) close to the mean values. In the same x-ray, the positions of the gonion for all subjects are displayed with triangles, the positions of the apophysis geni with squares and the positions of the incisor with circles. All of them have been measured with respect to the center of the condyle using the occlusal plane as the horizontal line. In order to classify these points, three new coordinate systems have been set, parallel to the global one, with their origin on the points with mean x-y values (In, Ge, Go). Each coordinate system defines four quadrants, each bounded by two half-axes. Fig. 4a shows the point with mean x-y values in each quadrant for the incisor (In1, In2, In3, In4), apophysis geni (Ge1, Ge2, Ge3, Ge4) and gonion (Go1, Go2, Go3, Go4). In addition, four more points with extreme values in x and y (Upper, Lower, Front and Back) have been analyzed (Fig. 4b). These

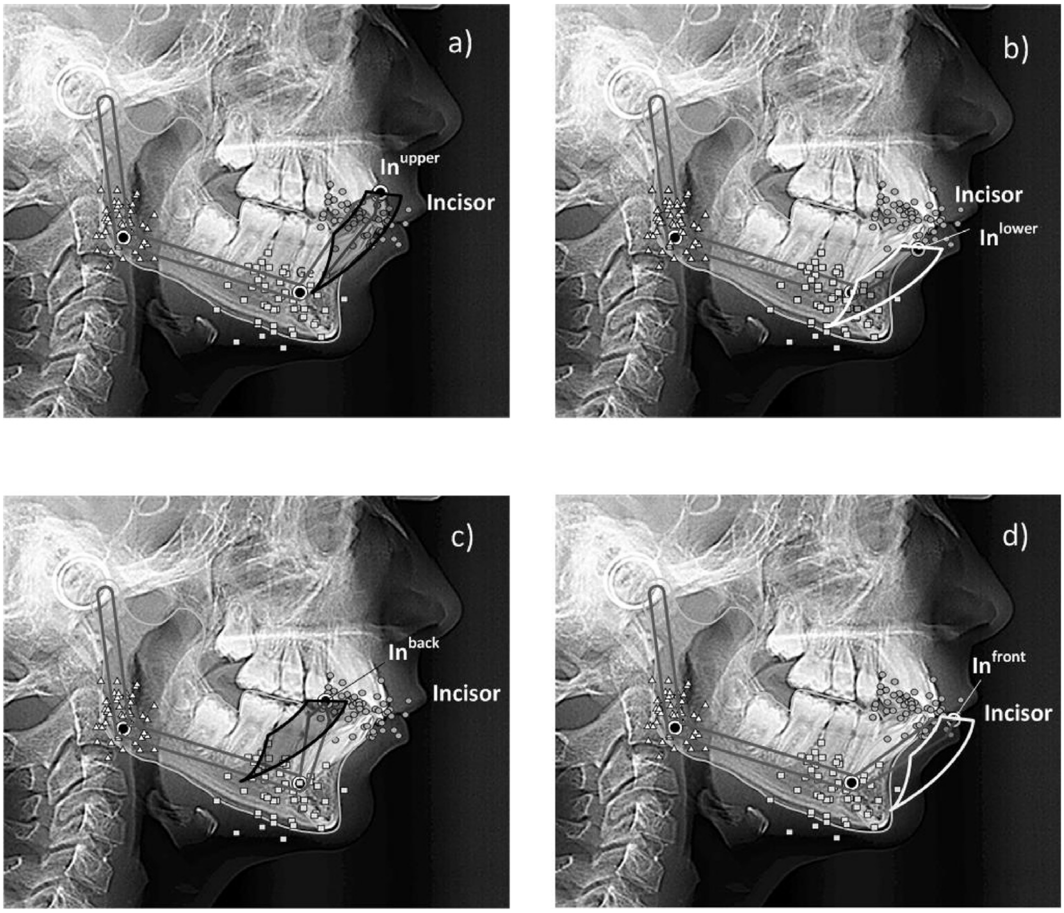



**Fig. 5.** (a) Border movement diagram for position $In^{upper}$ of the lower incisor. (b) Border movement diagram for position $In^{lower}$ of the lower incisor. (c) Border movement diagram for position $In^{back}$ of the lower incisor. (d) Border movement diagram for position $In^{front}$ of the lower incisor.

points have been chosen because in this case the difference between the distances from the condyle to each point is greater and the results are clearer. For each one of all these points, angles $\theta_{In}$, $\theta_{Ge}$ and $\theta_{Go}$ have been measured in order to compare the influence of morphology variations on the displacements of different areas of the mandible.

On the other hand, Table 2 shows the mean values of maximum protrusion, retrusion and interincisal distance of each subject. The protrusion and retrusion values are measured with a George Gauge with a 5-mm bite fork. Coordinate *y* of the lower incisor tip coincides with the bite thickness.

Using the results shown in Fig. 3, from here on, this article develops a study on the changes in the borders of the envelope of motion of the lower front teeth, apophysis geni and gonion. The position of the analysed points with respect to the condyle depends on the lengths of the ramus and the body of the mandible, the angle between them and the height of the body of the mandible. Within the studied group, angles $\theta_{In}$, $\theta_{Ge}$ and $\theta_{Go}$ have been compared.

### *3.1. Movement of the lower incisor in subjects with different morphologies*

Table 3 shows the mean value of angle $\theta_{In}$ for the 52 subjects grouped by quadrants as explained above. It can be observed that the first quadrant has the maximum value for this angle. This implies that the pattern of movement is more vertical, that is, when opening the mouth, the incisor moves more vertically. In the case of the third quadrant, angle $\theta_{In}$ has the lowest value, which implies that the movement pattern is more horizontal, that is, the incisor moves more horizontally.

Table 4 shows angle $\theta_{In}$ for the mandibles with extreme positions. When we compare the upper and lower positions, it can be observed that in the mandible corresponding to position $In^{Lower}$, the angle is lower. In this case, the incisor moves more in a horizontal direction and less in a vertical direction. Nevertheless, in the mandible corresponding to position $In^{Upper}$, the incisor moves less horizontally and more vertically (Fig. 5a and b). Finally, the two mandibles with extreme horizontal positions are compared. In the mandible corresponding to position $In^{Front}$, the angle is higher, which implies that the incisor moves less horizontally and more vertically (Fig. 5d). On the other hand, the mandible corresponding to position $In^{Back}$ has a lower $\theta_{In}$ angle. Therefore, it moves more horizontally and less vertically (Fig. 5c).

These four individuals have different lengths and angles for the incisor-condyle line. Consequently, their border diagrams are different as shown in Fig. 5a–d.

### *3.2. Movement of the apophysis geni in subjects with different morphologies*

A similar study has been carried out for the position of the apophysis geni. Again, the occlusal plane is considered to be horizontal. In this case, the border movements of the apophysis geni have been calculated and the values of angle $\theta_{Ge}$ have been compared for all the analyzed points. The pattern of the results is

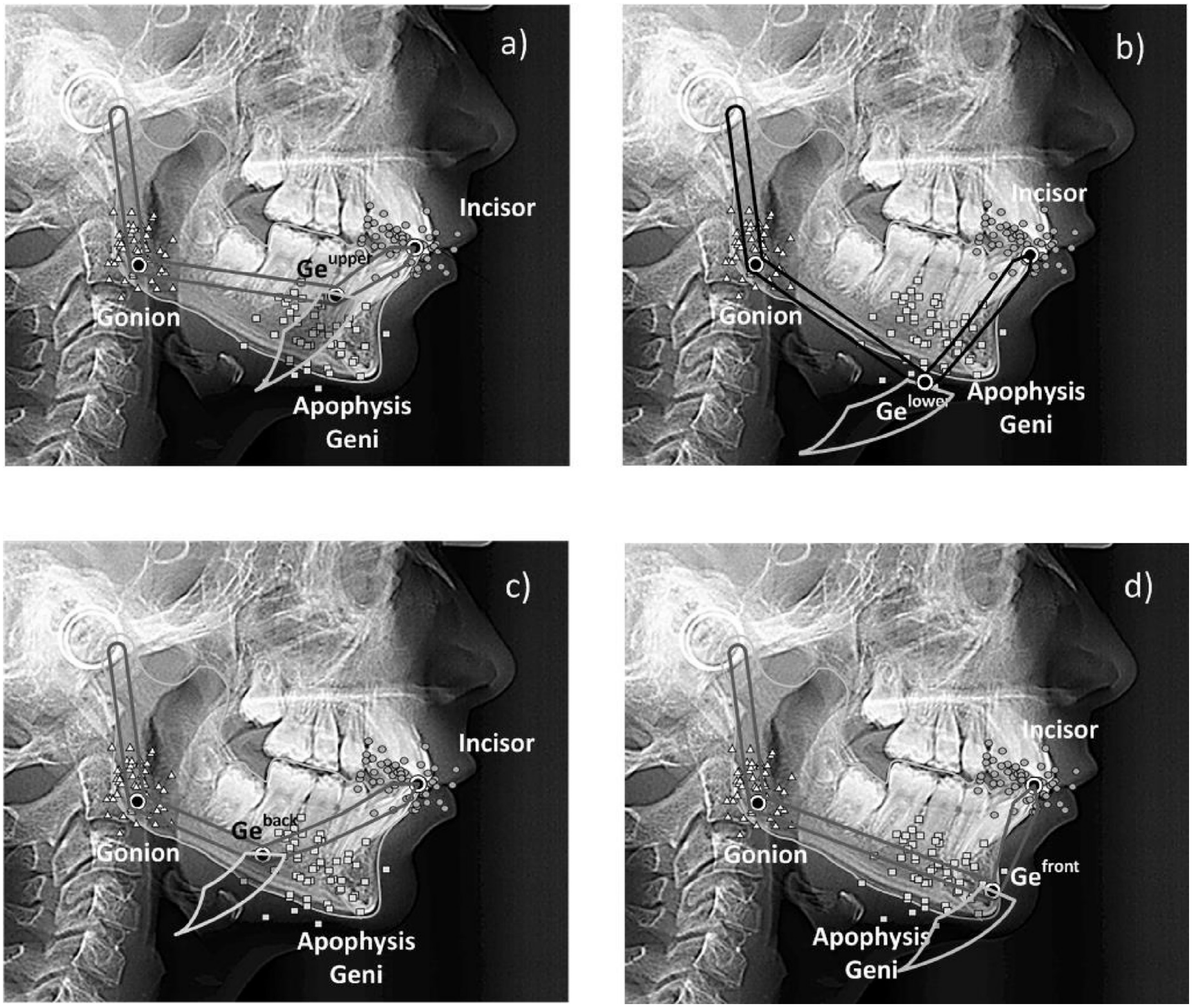



**Fig. 6.** a) Border movement diagram for the upper position of the apophysis geni. b) Border movement diagram for the lower position of the apophysis geni. c) Border movement diagram for the back position of the apophysis geni. d) Border movement diagram for the front position of the apophysis geni.

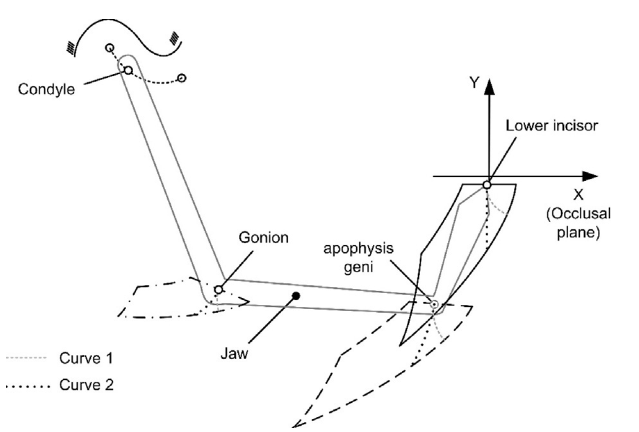



**Fig. 7.** Curves for a MAD design. Curve 1 represents a protrusive displacement of the lower incisor and the apophysis geni. Curve 2 represents a movement that maintains the protrusion of the incisor but produces a backward movement of the apophysis geni and the gonion.

the same as for the incisor. In the mandibles corresponding to positions $In^{Lower}$ and $In^{Back}$, the angle is lower and the apophysis geni moves more in a horizontal direction (Fig. 6b and c). In the mandibles corresponding to positions $In^{Upper}$ and $In^{Front}$, the apophysis geni moves more vertically (Fig. 6a and d).

### *3.3. Movement of the gonion in subjects with different morphologies*

Although the movement of the gonion is less relevant when designing a MAD, it can also be interesting to know its movement pattern. For this reason, it has been studied in the same way as the incisor and the apophysis geni and the results obtained are shown in Appendix A.

## 4. Discussion

This paper describes the changes in form and size of mandibular border movements in the sagittal plane at different points of mandibles with varied shapes. The prediction of the movement of different mandibular points by means of the mathematical model presented in this work could allow a greater personalization in the design of MADs [42]. The control of mandibular movements during sleep while using a MAD seems important since uncontrolled opening could cause a posterior rotation of the jaw leading to more posterior positions, narrowing the upper airway and increasing the resistance to air flow [45–48].

Mandibular movements in the sagittal plane show a variability depending on the location of the point that is analyzed. The border movement diagrams of the lower front teeth are more vertical while the ones of the apophysis geni (point Ge) are more horizontal (Figs. 5 and 6 and A.1). Consequently, mouth opening may cause point Ge to move backward more than the lower front teeth and it may not protrude when the incisors do. This is important, since the biggest masses of upper airway soft tissue (genioglossus muscle) are inserted in the apophysis geni and a backward movement of this area could narrow the airway [8,33,49–51]. Some researchers suggest that the increase in mouth opening can decrease the level of effectiveness of a MAD [6,39,42,43,52].

Considering this in connection with the performance of a MAD, we should be aware that, when using it, the mouth remains slightly open. This causes a certain degree of retrusion in the incisor and an even greater retrusion in the area of the apophysis geni. This retrusion is usually compensated by the protrusion induced by the MAD. The balance is usually a net forward movement of the incisor (in the anteroposterior direction). However, the movement of point Ge is less forward, null or even backward. Consequently, the fact that the lower front teeth protrude, does not mean that the apophysis geni will protrude the same length.

On the other hand, variations in mandibular morphology imply differences in movement patterns of the analyzed points of the mandible. In the Neelapu meta-analysis [12], it is concluded that high values of the lower anterior facial height (distance from the anterior nasal spine to the lowest point of the menton) predispose to OSAS. According to the mandibular kinematic model described in this paper, in subjects with high values of lower anterior facial height, like dolichocephalic and retrognathic subjects, mouth opening predisposes to the retrusion of the Ge point. Hence, the model can explain Neelapu's conclusions.

According to Guarda-Nardini's systematic review [14], patients with a reduced lower anterior facial height and a reduced mandibular plane angle (ie, brachyfacial pattern) tend to respond better to MAD treatment. This is consistent with the fact that in these patients MADs can easily produce a net forward movement of point Ge, due to a very slight backward movement during mandibular opening, as predicted by the kinematic model described in this paper.

These facts may help to understand why not all mandibles protrude equally when using a MAD. It may also explain why airway obstruction is higher in certain subjects than in others when opening their mouth during sleep. The fact that some patients may have a backward movement of the Ge point after inserting a MAD in their mouth could explain, in part, why the apnea/hypopnea rate of a small percentage of patients gets worse when using a MAD.

The design of a MAD should consider the pattern of each patient's mandibular movements [42]. The position of the areas of the jaw that are important in relation to upper airway patency when using a MAD should be studied for each patient. This could lead to an individualized design to find favorable positions of these areas. On the other hand, MAD design should control mouth opening so that, for its maximum value, the anterior mandibular area moves forward or, at least, does not move backward (Fig. 7). In relation with this, the following issues have to be considered:

- When a MAD is inserted, the mouth remains slightly open and this causes a mandibular retrusion at the dental level and in the posterior area of the symphysis menti.
- There can be dental protrusion and a simultaneous backward movement of the apophysis geni and the gonion due to their lower location with respect to the condyle.

## 5. Conclusions

In this work, we apply a kinematic model to study the differences in mandibular movement for different morphologies. Several relevant points have been studied such as the lower incisor, the apophysis geni and the gonion. The kinematic model can predict the mandible kinematic behavior of each patient using measurements taken directly from the patient and from a lateral x-ray. Based on the analysis of the results, we conclude that:

1. The use of a mathematical model shows the influence of mandibular morphology in the movements in the sagittal plane.
2. Mouth opening has a greater tendency to produce a backward movement in those areas located in a lower and posterior position with respect to the mandibular condyle.
3. The prediction of the movement of different mandibular points by means of the mathematical model presented in this paper can simplify the methodology in finding an optimal mandibular positioning with a MAD.
4. The individual analysis of the size and shape of the mandible may help to understand that untreated OSA patients might be differently affected by mouth opening during sleep.

## Author contributions

Marcos Garcia, Juan A. Cabrera and Alex Bataller conceived the idea and performed the mandibular movement model to carry out the experiments. Javier Vila and Pedro Mayoral carried out the lateral cephalometric x-rays and identified the relevant points in them. The manuscript and all figures were written and drawn by Marcos Garcia, Juan A. Cabrera and Alex Bataller, respectively. All authors discussed and commented the results of the manuscript.

## Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the ethical review board of the Alfonso X University in Madrid. UAX-2016-021.

## Informed consent

Informed consent was obtained from all individual participants included in the study.

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## Conflict of interest

The authors declare no competing interests.

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: https://doi.org/10.1016/j.sleep.2020.04.016.

## Appendix A

### Movement of the apophysis geni in subjects with different morphologies

The mean value of angle $\theta_{Ge}$ for the 52 subjects grouped by quadrants is shown in Table A.1. It can be seen that the pattern of the results is the same as for the incisor. The first and third quadrants have the maximum and minimum value for $\theta_G$ respectively. This implies that for the mandibles with the incisor in the first quadrant, the movement pattern of the apophysis geni is more vertical, retruding less than the other mandibles, while the jaws corresponding to the third quadrant retrude more than the rest.

**Table A.1**
Mean values of angle $\theta_{Ge}$, x and y distances between the condyle and the apophysis geni of the 52 subjects grouped by quadrants.

| Quadrant | Apophysis geni | | | | | |
|---|---|---|---|---|---|---|
| | $\theta_{Ge}$ (°) | SD | X (mm) | SD | Y (mm) | SD |
| 1 | 47.16 | 2.81 | 76.43 | 6.68 | −73.16 | 4.84 |
| 2 | 43.37 | 2.25 | 63.32 | 4.36 | −68.57 | 5.70 |
| 3 | 41.37 | 3.07 | 62.93 | 5.75 | −87.07 | 6.10 |
| 4 | 42.47 | 4.59 | 77.44 | 4.22 | −88.44 | 6.24 |

Table A.2 shows angle $\theta_{Ge}$ for the mandibles with extreme positions. Again, the pattern of the results is the same as for the incisor. In the mandibles corresponding to positions $In^{Lower}$ and $In^{Back}$, the angle is lower and the apophysis geni moves more in a horizontal direction (Fig. 6b and c). In the mandibles corresponding to positions $In^{Upper}$ and $In^{Front}$, the apophysis geni moves more vertically (Fig. 6a and d).

**Table A.2**
Values of angle $\theta_{Ge}$, x and y distances between the condyle and apophysis geni of the four mandibles with extreme vertical and horizontal positions of the apophysis geni among the 52 subjects studied.

| Extreme position | Apophysis geni | | |
|---|---|---|---|
| | $\theta_{Ge}$ (°) | X (mm) | Y (mm) |
| Upper | 49.34 | 70.84 | −66.67 |
| Lower | 39.74 | 67.62 | −93.53 |
| Front | 46.48 | 91.11 | −78.71 |
| Back | 41.11 | 57.90 | −79.15 |

**Movement of the gonion in subjects with different morphologies**

The changes in the position of the gonion with respect to the condyle mainly depend on the length of the ramus. The mean points of the quadrants defined in the gonion and the points of extreme positions have been analyzed. The results show that all the studied points mainly move in a horizontal direction.

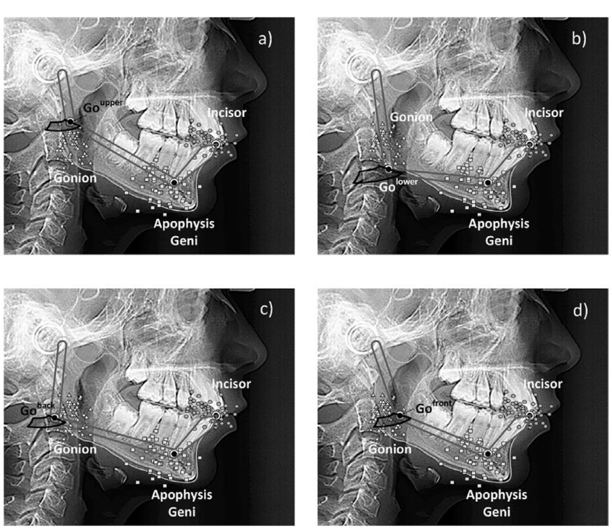


**Fig. A.1.** a) Border movement diagram for position $Go^{upper}$ of the gonion. b) Border movement diagram for position $Go^{lower}$ of the gonion. c) Border movement diagram for position $Go^{back}$ of the Gonion. d) Border movement diagram for position $Go^{front}$ of the gonion

The mean value of angle $\theta_{Ge}$ for the four quadrants is shown in Table A.3. It can be seen that the value of this angle is very low for all the positions. This means that the gonion mainly moves in horizontal direction in all cases. However, the points in quadrants 1 and 4 move slightly more vertically, retruding a little less than the points in quadrants 2 and 3.

**Table A.3**
Mean values of angle $\theta_{Go}$, x and y distances between the condyle and the gonion of the 52 subjects grouped by quadrants.

| Quadrant | Gonion | | | | | |
|---|---|---|---|---|---|---|
| | $\theta_{Go}$ (°) | SD | X (mm) | SD | Y (mm) | SD |
| 1 | 8.48 | 3.77 | 7.54 | 2.64 | −49.61 | 4.72 |
| 2 | 5.28 | 3.88 | 1.13 | 2.09 | −50.06 | 4.92 |
| 3 | 2.99 | 2.50 | −0.04 | 3.14 | −64.93 | 4.79 |
| 4 | 9.81 | 5.78 | 10.43 | 2.31 | −66.19 | 7.93 |

Table A.4 shows angle $\theta_{Go}$ and the horizontal (x) and vertical (y) distance between the condyle and the gonion.

It is observed that the x values of all points are very small. This is because the gonion is practically below the condyle. However, the vertical distance is remarkable, varying between 40.24 mm from the top point and 70.67 mm from the bottom point. Therefore, although there are barely any differences between the shapes of the border movement diagrams, there is a difference in size, being larger when the distance from the point to the condyle is greater (Figure A.1a-d). Therefore, the retrusion of the upper and lower points will be the lowest and largest respectively.

**Table A.4**
Values of angle $\theta_{Go}$, x and y distances between the condyle and gonion of the four mandibles with extreme vertical and horizontal positions of the gonion among the 52 subjects studied.

| Extreme position | Gonion | | |
|---|---|---|---|
| | $\theta_{Go}$ (°) | X (mm) | Y (mm) |
| Upper | 1.98 | 2.71 | −40.24 |
| Lower | 6.42 | 4.45 | −70.67 |
| Front | 9.16 | 12.39 | −57.23 |
| Back | 2.67 | −1.14 | −58.70 |

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