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ORIGINAL ARTICLE

Performance of Mandibular Advancement Devices When Opening the Mouth

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Abstract

Purpose The aim of this study is to evaluate the kinematic behavior of mandibular advancement devices (MAD) when opening the mouth, by analyzing the influence of the coupling system between the splits and the patient's morphology.

Methods Seven widely used MADs with different coupling mechanisms have been studied in 21 patients (8 females, 13 males). Using validated mathematical MAD models, one per tested device, the trajectories of the lower incisor and the posterior chin area (apophysis geni) were simulated for each device when opening the mouth.

Results The results show that all MADs maintain mandibular advancement with the mouth closed. However, significant variations occur when the mouth is opened. Devices with bars maintained mandibular advancement more effectively than those with fins, although performance depended on the bars' length and joints' position. In particular, shorter bars and more forward-positioned joints resulted in greater protrusion. Devices with fins consistently caused mandibular retrusion when opening the mouth.

Conclusion It is not possible to reach general conclusions about the effectiveness of MADs by analyzing any device. Rather, the results obtained are for a specific MAD and may be different for another MAD model. The study also found that mandibular movement patterns differed according to patients' facial biotypes. The results suggest that both the coupling system and patients' morphology must be considered in the design of MADs to maintain effective mandibular advancement during mouth opening.

Keywords Mandibular advancement device (MAD) · Mandibular kinematics · MAD effectiveness · MAD design

Introduction

The treatment of obstructive sleep apnea (OSA) with mandibular advancement devices (MADs) is a well-recognized option that has demonstrated a significant reduction in the apnea-hypopnea index (AHI) and associated symptoms [1, 2]. MADs act by repositioning the mandible in a new vertical and anteroposterior position, augmenting the oropharyngeal and hypopharyngeal airway during sleep. By keeping the lower jaw in this position, MADs prevent collapse of the upper airway [3, 4].

Currently, a wide variety of MADs are available. They can be classified as one-piece devices (monobloc) or two-piece devices (bibloc or twinbloc). In monobloc devices the upper and lower splints are joined together as a single piece, so that they do not allow movement of the jaw while in use. Two-piece devices are composed of an upper and a lower splint joined by a coupling mechanism that allows some type of anteroposterior, vertical and lateral movement of the mandible while in use. Different elements are used in the coupling mechanism, such as rigid rods or bars, telescopic rods or bars, screws, elastic straps and fins or cams [5]. All these coupling mechanisms allow regulating the degree of initial mandibular advancement with the mouth closed, but when opening the mouth, they present differences in the anteroposterior movement of the mandible.

MADs are initially set with a protrusion between 0 and 75% of the patient's maximum mandibular advancement.

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This position is referred to as the starting point (SP) and it varies over time depending on the patient's response to treatment. On the other hand, MADs have an interincisal opening prescribed by a qualified dentist with a minimum value that depends on the manufacturing requirements of the device. This vertical opening usually ranges between 2 and 8 mm [6, 7].

The mandible moves with a wide range of movements that depend on the temporomandibular joint and are limited and controlled by the muscles, joint capsule and ligaments [8, 9]. Anteroposterior and superoinferior movements of the mandible can modify the caliber of the upper airway [10, 11]. These movements follow a common pattern that can be studied by tracing the path of a point on the mandible, such as the tip of the lower central incisor or the chin. The incisor movement pattern was first studied by Posselt [12]. García et al. used Posselt's diagram to analyze mandibular movement in individuals with different craniofacial patterns [13]. The study of the movement of the posterior chin area (apophysis geni) is particularly interesting, since in this area the main lingual muscles, responsible for the opening of the airway, join the mandible [14]. Therefore, when evaluating the kinematic behavior of a MAD, it seems important to analyze the movement that occurs in the apophysis geni and evaluate its effect on the position of the lingual muscles when patients open their mouths.

In addition, the patient's morphology is important in the movement of the incisor, the apophysis geni, or other points of the mandible. Studies have shown that certain mandibular morphologies (retrognathia, dolichofacial growth pattern) predispose to OSAS [15]. Other studies find associations between mandibular morphology and the probability of positive response to treatment with MADs [16, 17]. However, there is a lack of studies on mandibular kinematics to explain the reason for these findings. Multiple papers record mandibular movement [18–22] and predict mandibular kinematics [23–25], but there are barely any studies on mandibular movement when using a MAD [26]. The movement of the mandible with a MAD depends on three aspects: the coupling mechanism, the temporomandibular joint, and the patient's morphology [27]. Therefore, the kinematic behavior of the mandible when using a MAD is different for each patient and for each MAD. Despite the importance of this, to the best of our knowledge, there is no published work comparing the mandibular kinematics of different patients using different MADs.

In this work, the movement at different points of the mandible when using a MAD is studied. For this purpose, 7 widely used MADs with different coupling mechanisms were selected and tested in 21 patients, of which 8 were female and 13 were male. All patients had complete dentition and symmetrical bone morphology.

Materials and Methods

The trials were performed on 21 patients, 8 women and 13 men, using 7 virtual MAD models, developed and validated in a previous work [26]. Using these virtual models makes it possible to study the devices without manufacturing them for every patient and testing jaw movement individually. This approach not only allows rapid and straightforward analysis of a large number of devices, but also enables the prediction of how a particular MAD will behave kinematically in a specific patient when opening the mouth.

The tested MADs were Narval, Somnodent Avant, Panthera, Orthoapnea Classic, Herbst, SomnoDent Flex and Micro2. Ethics approval was obtained from the Universidad Católica de Murcia research ethics board (TC/14-24) and written consent to participate was obtained from every patient whose data were used for this study in accordance with the Declaration of Helsinki and its later amendments.

The first step was to perform the measurements required to define the mathematical models of each patient's mandible wearing each MAD. All measurements were taken in the sagittal plane projection. With these data, the kinematic behavior of each of the MADs in each of the patients was simulated. The process carried out is explained in the following sections:

Records Taken from Patients

Each patient underwent a Cone Beam Computed Tomography (CBCT) with an open bite, as well as a lateral X-ray. The bite registration of each patient was taken with a George gauge with 5 mm of vertical interincisal opening and the range of mandibular advancement was measured from maximum retrusion to maximum protrusion (total avancement).

Measurements on the CBCTs and Radiographs

The scale typically included on the side of X-rays was used to calculate the scale and obtain accurate measurements. In order to verify the measurements on both the X-ray and the CBCT, the scale of a patient's X-ray, once determined, was used to calculate the scale of the CBCT, since in this case there is no scale bar available to obtain real measurements.

The apophysis geni was identified in the posterior chin region and the mandibular lengths ML_1 and ML_2 of each patient were measured from the geometric center of the condyle to the tip of the lower incisor and the apophysis geni, respectively. The occlusal plane was defined as a straight line from the edge of the lower incisor to the tip of the cusp of the first molar of the mandible (Fig. 1).

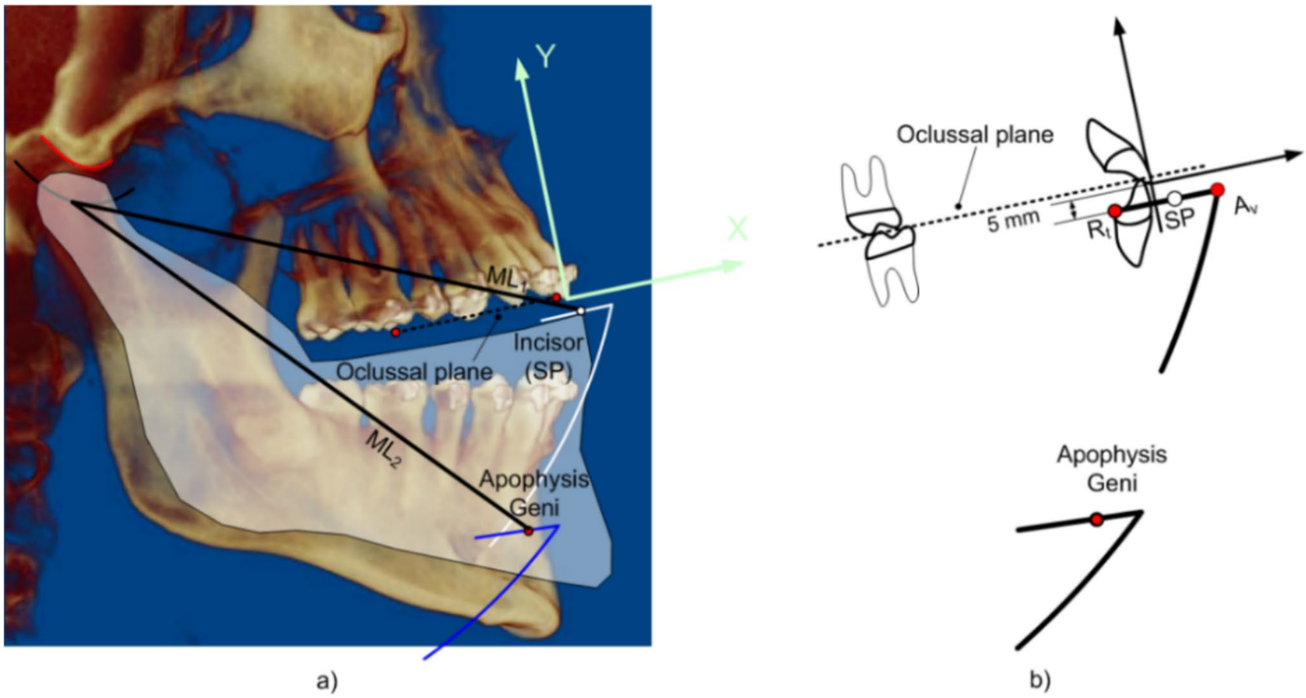

Fig. 1 **a** Mandibular lengths from the condyle to the incisor (ML_1) and to the apophysis geni (ML_2). Upper and anterior borders of Posselt's diagram for the lower incisor in white and for the apophysis geni in blue. **b** Close-up of the upper area of Posselt's diagram

An XY coordinate system was placed with the abscissa axis aligned with the occlusal plane and its origin at the tip of the upper incisor. This coordinate system was used to define the position of the different points considered in this study (Fig. 1).

The glenoid cavity of the maxilla was identified and the curve that defines the profile of the articular fossa was mathematically determined [26]. From this curve (in red in Fig. 1a) the trajectory of the geometric center of the condyle was obtained considering that the perpendicular distance to the glenoid curve remained constant. This trajectory is shown in Fig. 1a in black.

Using the methodology defined by [28], the upper and anterior borders of Posselt's diagram were obtained for each patient with 5 mm of vertical distance between the tip of the upper incisor and the occlusal plane (Fig. 1b). This distance corresponds to the thickness of the George gauge used to measure the maximum mandible retrusion (R_t) and maximum advancement (A_v). The starting point considered was 60% of the distance between R_t and A_v, which is equivalent to 60% of the total jaw advancement.

In addition, the upper and anterior borders of Posselt's diagram were also defined for the apophysis geni located in the chin area of the mandible. As mentioned above, the movement of this point is especially relevant since the geniohyoid muscle, one of the main upper airway dilator muscles, extends from the hyoid to the symphysis of the chin.

Measurements on the Devices

For each MAD with bars (Narval, Somnodent Avant, Panthera, Classic and Herbst), points O_2 and A, where the bar is joined to the maxillary and mandibular splints, respectively, were identified. The distance between these two points was measured to obtain the length of the bar O_2A. The angle between this bar and the occlusal plane of the device was also measured (Fig. 2a). Fig. 2b shows the SomnoDent device fitted on the dental arches and Posselt's diagram with the starting point (SP) on the upper border.

For MADs with fins or cams (SomnoDent Flex and Micro2), the procedure was as follows:

- The occlusal plane of the device (in red in Fig. 2c, d) and the initial and final points of the cam (A and D) were identified in both devices. The horizontal and vertical distances of the cam on the SomnoDent Flex device were then measured (d and h in Fig. 2c). In the case of the Micro2 device, the angle between the cam and the occlusal plane is 90°. Therefore, the horizontal distance (d) is 0 and the vertical distance (h) is equal to AD (Fig. 2d).
- Next, the horizontal distance (Di) between the initial point of the cam (A) and the tip of the lower incisor was measured.

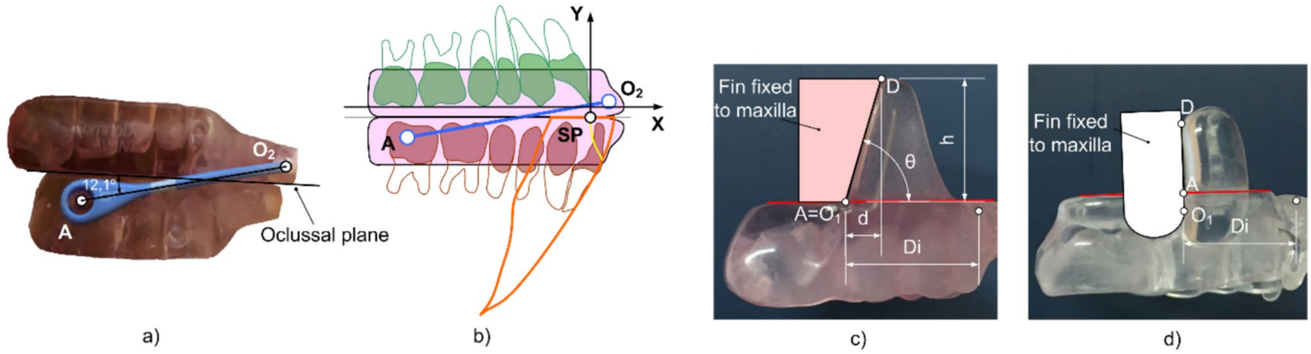

Fig. 2 **a** Angular position of bar O_2A on the SomnoDent Avant device. **b** SomnoDent device fitted on the dental arches **c** Measurements on the SomnoDent Flex device. **d** Measurements on the Micro2 device

- With the aforementioned measurements, the lower cam was positioned with respect to the lower incisor and the occlusal plane. To position the upper cam, the AO_1 distance measured in the two devices was used with the two splints placed one on top of the other as if they were in the mouth.

Virtual Assembly of the Devices

The virtual placement of the devices with bars in the mouth was carried out by using the angle between the O_2A bar and the previously measured occlusal plane and by placing the mandible in a position with 5 mm of vertical opening between the incisors and 60% advancement of the lower incisor (Fig. 3a).

Similarly, the lower splint of the devices with cams was placed with 60% of the patient's total jaw advancement and 5 mm of vertical opening between incisors (see Fig. 3b). The previously taken measurements (Fig. 2c, d) were then used to place the upper cam of the device with its end at point O_1.

Virtual Movement of the Devices when Opening the Mouth

Once the device was placed in the mandible, the mouth was opened and the trajectory of the analyzed point (tip of the lower incisor or apophysis geni) was studied.

- Devices with bars. The mouth was opened until the analyzed point reached the anterior border of Posselt's diagram (see Fig. 4a). In the case of the Herbst device, in order to obtain the trajectory of the incisor and apophysis geni, the length of bar O_2A was kept constant. In this device, patients can vary the length of the O_2A bar, but during sleep, the muscles and ligaments relax and patients do not unconsciously advance the device. This assumption is based on the neurophysiology of sleep,

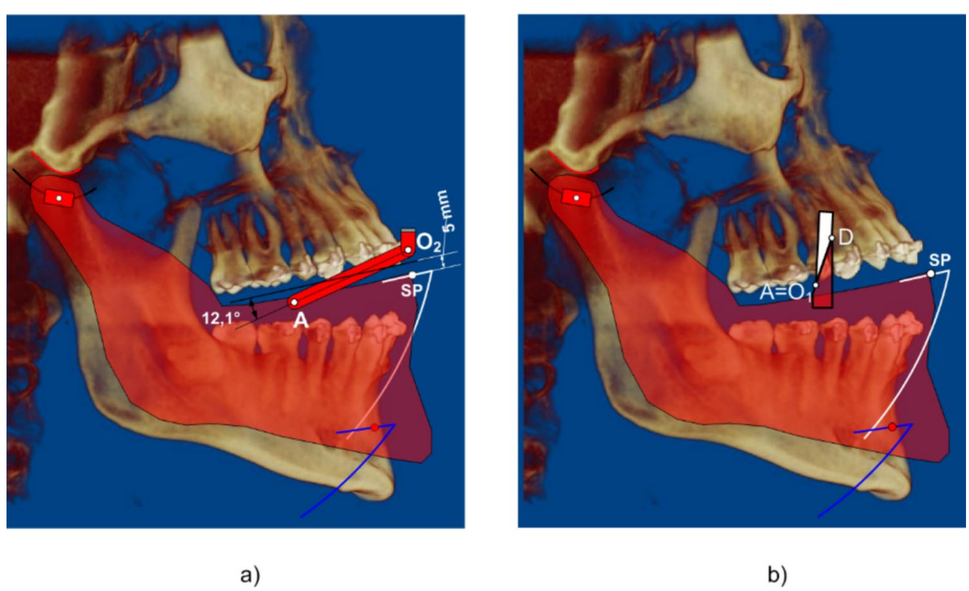

Fig. 3 Virtual assembly of the **a** SomnoDent Avant device, **b** SomnoDent Flex device

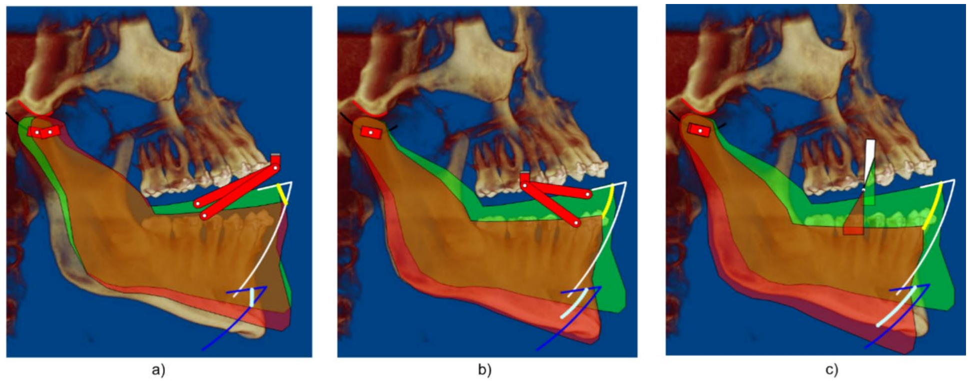

Fig. 4 Posselt's diagrams for the incisor (in white) and for the apophysis geni (in blue). Trajectories of the lower incisor (in yellow) and the apophysis geni (in light blue) when opening the mouth with the **a** SomnoDent Avant device, **b** Herbst device, **c** SomnoDent Flex device

during which generalized hypotonia occurs due to the brainstem's active inhibition of the trigeminal motor nucleus [29]. As shown in Fig. 4b, when opening the mouth with the Herbst device, the analyzed points moved backward and did not contact the anterior border of Posselt's diagram.

- Devices with fins or cams. With these devices, there was a retrusion of the mandible when the mouth was opened, so that the incisor did not reach the anterior border of Posselt's diagram. Thus, the movement was analyzed until the contact between the two cams ended, that is, until point O_1 reached the position of point D (Fig. 3b). In the results tables, this position was considered as the maximum opening allowed by the device, since from that instant the upper cam was no longer in contact with the lower one and, consequently, the device stopped working. In Fig.4c the initial position of the jaw is shown in green and the final position, at the moment when the contact between the cams ends, is shown in red.

Analysis of the Movement of the Incisor and the Apophysis Geni

In order to determine whether the movement of the analyzed point was a forward or backward movement, the superior and anterior borders of Posselt's diagram were plotted (in red in Fig. 5) and a vertical line was traced through the starting point. This line was used to measure the deviation with respect to the vertical at the end of the mouth opening, reflecting the protrusion or retrusion of the mandible at the analyzed point. On the other hand, the mouth opening was measured as the vertical distance from the initial position to the final position of the trajectory (Fig. 5). All these measurements were performed for the 21 patients and are shown in the results section. It should be noted that the curve followed by the analyzed points can be backward, forward, or backward–forward. If the movement of the point is forward, the deviation with respect to the vertical is positive (Fig. 5a). If the movement is backward, the deviation is negative (Fig. 5b). Finally, if the movement is initially backward, but ends up being forward, the deviation starts as negative and ends up being positive (Fig. 5c).

Given that the primary purpose of a MAD is to reposition the jaw in a forward position to keep the upper airways open during sleep, the jaw moving backward when the mouth is opened could be considered an indication that the device is not working properly. Therefore, this study considers that a MAD has better behavior when it does not cause the jaw to move backward upon opening the mouth. Similarly, it can also be considered that the effectiveness of MADs that maintain the jaw in an advanced position will be greater than that of those causing mandibular retrusion.

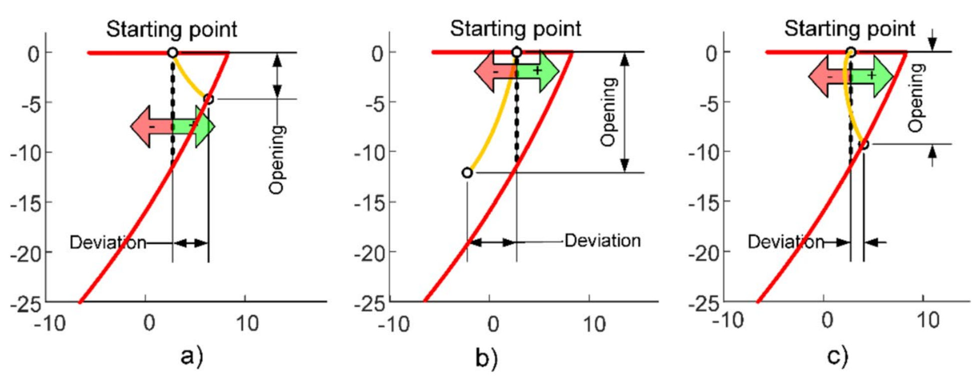

Fig. 5 Upper area of Posselt's diagram in red. The yellow curve represents the trajectory of the analyzed point on the mandible when the patient opens the mouth with the device. **a** Forward movement. **b** Backward movement. **c** Backward–forward movement

Results

The trajectory followed by the tip of the lower incisor has been studied first, since this point is the one traditionally used to draw Posselt's diagram. Additionally, the trajectory of the apophysis geni has also been studied, verifying whether when the mouth is opened, its position moves forward or backward with respect to its initial position when the mouth is closed.

Results for the Lower Incisor

Fig. 6 shows the trajectory of the lower incisor for each patient with all the analyzed devices in different colors. The figure allows observing, on one hand, the difference in the performance of each of the analyzed MADs in the same patient when opening the mouth and, on the other hand, the variability of the performance of the same device in different patients. The same figure shows notable differences in the length of the upper border of Possel's diagram among different patients (corresponding to the total advancement measured with the George gauge), as well as in the inclination of the anterior border.

Table 1 presents the results for the incisor when opening the mouth with the devices coupled with bars. The values shown in the table are: the total advancement measured with the George gauge (TA), the maximum opening achieved with the device (A), the incisor deviation from its initial position with respect to the vertical (B), and the type of curve described (C). The box for the B value is highlighted in green in the cases in which the incisor advanced when opening the mouth and in red in the cases in which it moved backward. On the other hand, the type of curve C can be protrusive (P) when the point consistently moves forward, retrusive (R) when there is a backward movement along the entire trajectory and retrusive–protrusive (R–P) when the point starts the trajectory with a small backward movement, but ends it in a more advanced position.

Table 1 shows that for the Classic and SomnoDent Avant devices, all patients have a protrusive curve similar to the one shown in Fig. 5a, producing an advancement of the incisor with respect to the SP. Although all patients have a protrusive movement when opening the mouth with these two devices, there are differences in the deviation with respect to the vertical, reaching a deviation ranging from 1.5 mm in patient #1 to 5.2 mm in patient #19 in the case of the Classic device, while this difference is smaller in the case of the SomnoDent Avant, varying from 0.8 mm in patient #1 to 2.9 mm in patient #19. These marked differences are mainly related to the patients' total advancement. Indeed, if we calculate the ratio between the advancement produced by the device and the total advancement of the patient, the differences are much smaller. In the case of the Classic device, the relative deviation goes from 21% in patient #1 to 31% in patient #19 while in the case of the SomnoDent Avant device, the deviation varies from 11% in patient #1 to 16% in patient #19.

In the case of the Narval and Panthera devices, all patients have a retrusive or retrusive–protrusive curve. That is, some of the devices have protrusive behavior when patients open their mouths to the maximum opening allowed by the device, but in intermediate positions, there is a backward movement of the incisor while in the remaining patients, retrusive behavior is observed from the beginning. The variation among the patients is also noteworthy. It is observed that the same device used by different patients performs differently. For example, for the Narval device, patient #21 has an backward incisor movement of − 0.5 mm, while patient #19 has a final incisor advancement of 0.3 mm. However, for the Panthera device, patient #20 has the greatest backward incisor movement (− 0.3 mm) while patient #19 has the greatest forward movement (0.6 mm). Therefore, these results indicate that, while in some patients the studied devices work properly, in others the incisor moves backward with respect to the initial position during the opening trajectory, thus producing a retrusion of the mandible. Finally, Table 1 also shows the results of the Herbst device. As can be seen, all patients have a retrusive curve when opening their mouths. As indicated above, this device has been simulated with the fixed O_2A bar length. In this case, the backward incisor movement ranges from 7.1 mm for patient #13 to 6.4 mm for patient #14.

Regarding the devices with fins, Table 2 shows the results obtained for the lower incisor. It can be seen that both devices produce a retrusive curve of the incisor in all patients when opening the mouth (see Fig. 5b). In addition, the final deviation with respect to the vertical is remarkable in all the individuals although considerably more pronounced in the case of the SomnoDent device. The maximum retrusion occurs in patient #6, for whom the SomnoDent Flex device produces a backward motion of the incisor of − 13.4 mm, while with the Micro2 device, it is − 1.8 mm.

Results for the Apophysis Geni

In order to analyze the trajectory of the apophysis geni when opening the mouth, a diagram was first generated with the superior and anterior borders of the movement limit of this point [13]. Fig. 7 shows this diagram in black for all patients. It can be seen how the inclination of the anterior border is considerably greater than in the incisor diagram (Fig. 6). This is due to the fact that the apophysis geni is in a lower

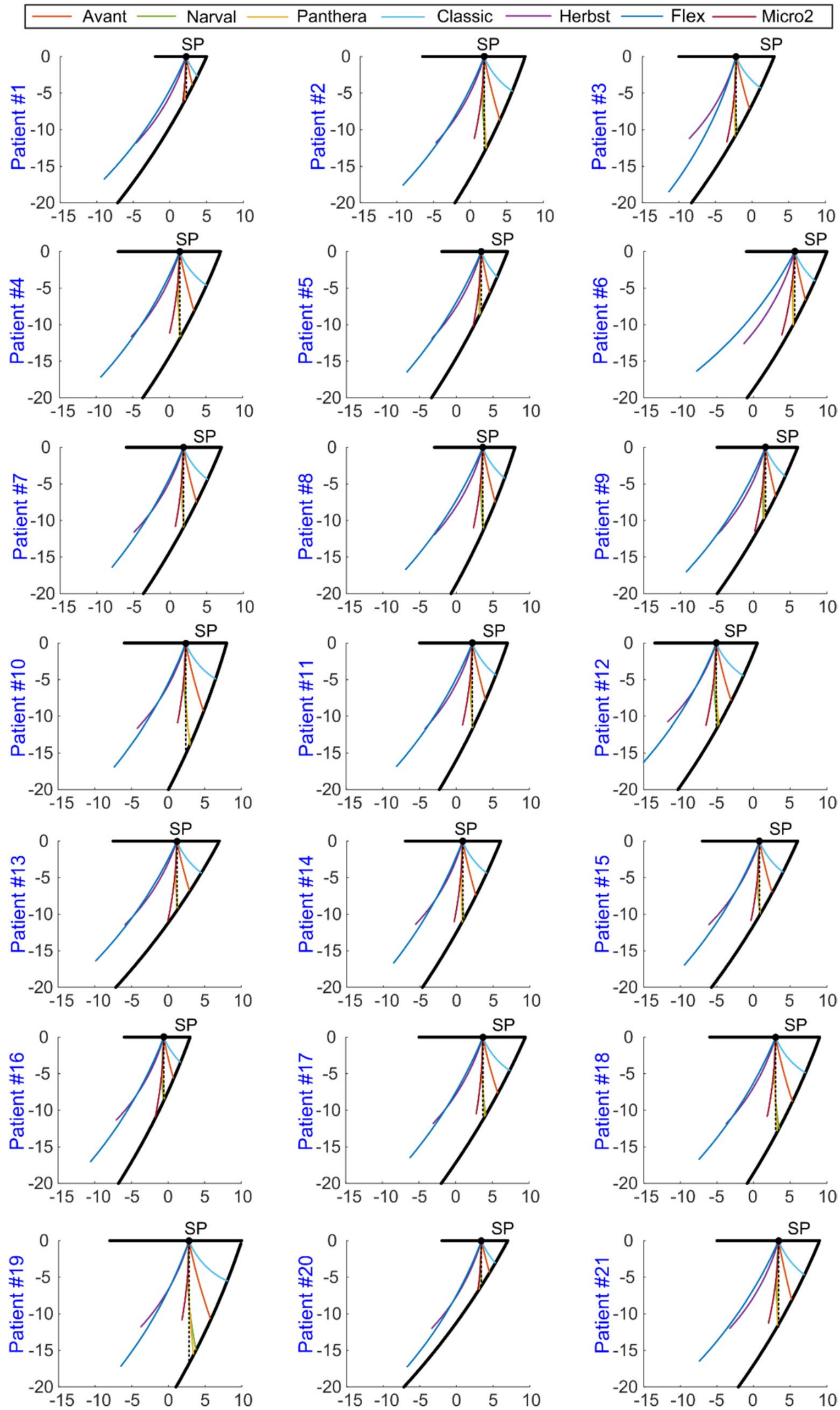

Fig. 6 Representation of Posselt's diagram for all patients and the trajectory of the lower incisor when opening the mouth with each of the devices

Table 1 Incisor results for the bar-coupled devices.)

		Classic			Avant			Narval			Panthera			Herbst		
Nr	TA	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	7	2.7	1.5	P	3.8	0.8	P	6.1	–	R	5.9	−0.1	R	11.9	−6.8	R
2	14	4.7	3.8	P	8.7	2.1	P	12.6	0.1	R–P	12.4	0.3	R–P	11.8	−6.6	R
3	13	4.2	3.3	P	7.0	1.8	P	11.0	−0.3	R	10.9	−0.1	R	11.2	−6.4	R
4	14	4.6	3.6	P	8.0	1.9	P	12.5	−0.4	R	11.8	−0.0	R	11.6	−6.6	R
5	9	3.4	2.2	P	5.5	1.1	P	8.9	−0.4	R	8.4	−0.2	R	11.9	−6.7	R
6	11	4.0	2.7	P	6.6	1.5	P	10.3	−0.4	R	10.0	−0.2	R	12.6	−6.9	R
7	13	4.4	3.3	P	7.5	1.8	P	11.3	−0.2	R	10.9	0.0	R–P	11.6	−6.7	R
8	11	4.2	2.9	P	7.5	1.7	P	12.0	−0.2	R	11.0	0.1	R–P	11.9	−6.6	R
9	11	3.9	2.7	P	6.7	1.4	P	10.1	−0.4	R	9.7	−0.1	R	11.8	−6.4	R
10	14	4.9	4.0	P	9.2	2.4	P	14.5	−0.3	R–P	13.9	0.6	R–P	11.6	−6.6	R
11	12	4.3	3.2	P	7.8	1.8	P	12.0	−0.2	R	11.7	0.0	R–P	11.7	−6.4	R
12	13.5	4.5	3.7	P	7.8	2.0	P	11.5	0.1	R–P	11.1	0.4	R–P	10.7	−6.6	R
13	14.5	4.3	3.3	P	6.7	1.7	P	9.7	−0.2	R	9.3	0.0	R–P	11.4	−7.1	R
14	13	4.4	3.3	P	7.4	1.8	P	11.3	−0.2	R	11.0	−0.0	R	11.4	−6.4	R
15	13	4.2	3.2	P	6.9	1.7	P	10.4	−0.2	R	9.8	0.0	R–P	11.4	−6.9	R
16	9	3.4	2.3	P	5.6	1.3	P	9.0	−0.2	R	8.5	0.0	R–P	11.3	−6.5	R
17	14.5	4.5	3.6	P	7.6	2.0	P	11.2	0.0	R–P	10.8	0.2	R–P	11.8	−6.8	R
18	15	4.9	4.0	P	8.8	2.3	P	13.3	0.0	R–P	12.7	0.2	R–P	11.8	−6.7	R
19	18	5.5	5.2	P	10.6	2.9	P	16.0	0.3	R–P	15.4	0.6	R–P	11.7	−6.5	R
20	9	4.2	3.2	P	6.2	1.7	P	9.4	−0.4	R	9.3	−0.3	R	12.0	−6.8	R
21	14	4.6	3.5	P	8.0	1.8	P	12.3	−0.5	R	11.5	−0.1	R	12.0	−6.6	R

TA total advancement [mm], ***A*** mouth opening [mm], ***B*** deviation with respect to the vertical [mm], ***C***:type of curve (Protrusive, Retrusive, Retrusive-Protrusive

position than the incisor with respect to the center of rotation, that is, with respect to the condyle. When opening the mouth with any of the analyzed MADs, less forward movement occurs for this point than for the incisor. This can be verified by comparing the trajectories obtained for these two points in Figs. 6 and 7.

Table 3 shows the results obtained for the apophysis geni in all patients wearing the devices coupled with bars. The calculated parameters are the same as for the lower incisor. That is, these are the total advancement (TA), the maximum opening achieved with the device (A), the incisor deviation from its initial position with respect to the vertical (B), and the type of curve described (C).

If we compare these results with those of the incisor shown in Table 1, the only device that maintains a protrusive curve in all patients is the Classic device, although a significant decrease in advancement is observed. For example, for patient #19, the deviation with respect to the vertical goes from 5.2 mm for the incisor to 4.4 mm for the apophysis geni. In the case of the SomnoDent Avant device, which has a protrusive curve at the incisor for all patients, at the apophysis geni, it becomes retrusive or retrusive–protrusive for most patients. The other devices—Narval, Panthera, and Herbst—have a retrusive pattern at this point, with a more pronounced retrogression than in the case of the incisor.

The results of the analysis of the apophysis geni in the devices with fins are shown in Table 4. All the curves are retrusive for the apophysis geni, with retrusion worsening in all cases when compared with those obtained for the lower incisor.

All data shown in the tables above indicate that in order to predict the behavior of a MAD, the patient's morphology would have to be taken into account in its design since, when opening the mouth, the same device produces different incisor trajectories in different patients.

Analysis of the Results

Differences between the seven treatment groups were analyzed using the non-parametric Friedman test. The results revealed statistically significant differences across the groups, $\chi^2 = 126.0$ for the lower incisor and $\chi^2 = 124.0$ for the gonion, $p < 0.001$ for both cases, indicating that the treatments produced distinct effects on the measured outcomes.

Table 2 Incisor results for the SomnoDent Flex and micro2 devices.

		SomnoDent Flex			Micro2		
Nr	TA	A	B	C	A	B	C
1	7	16.7	−11.2	R	11.2	−0.5	R
2	14	17.5	−11.1	R	11.2	−1.3	R
3	13	18.5	−9.1	R	11.6	−1.3	R
4	14	17.1	−10.7	R	11.1	−1.4	R
5	9	16.5	−10.1	R	11.1	−1.1	R
6	11	16.3	−13.4	R	11.4	−1.8	R
7	13	16.4	−9.7	R	10.8	−1.1	R
8	11	16.7	−10.5	R	11.0	−1.3	R
9	11	17.0	−10.8	R	11.4	−1.4	R
10	14	16.9	−9.7	R	10.9	−1.1	R
11	12	16.8	−10.3	R	11.2	−1.3	R
12	13.5	17.5	−11.0	R	11.2	−1.4	R
13	14.5	16.4	−11.1	R	10.9	−1.2	R
14	13	16.7	−9.4	R	11.0	−1.1	R
15	13	16.9	−10.2	R	10.8	−1.2	R
16	9	17.0	−10.0	R	10.9	−1.2	R
17	14.5	16.5	−9.9	R	10.5	−0.9	R
18	15	16.7	−10.5	R	10.8	−1.1	R
19	18	17.2	−9.3	R	10.8	−1.0	R
20	9	17.2	−10.1	R	11.3	−0.4	R
21	14	16.8	−10.8	R	11.3	−1.4	R

TA total advancement [mm], ***A*** opening [mm], ***B*** deviation with respect to the vertical [mm], ***C*** type of curve (Protrusive, Retrusive, Retrusive-Protrusive)

Discussion

The results of the present study with 21 patients, treated with 7 different devices, show how the design of each device and the facial biotype affect the protrusion or retrusion of the mandible when opening the mouth. The most important factor in the MAD design is the coupling system used between the upper and the lower splint. In this work, it has been demonstrated that devices with bars produce greater advancement at the analyzed points than those with fins. However, not all devices with the same coupling system have the same kinematic behavior. In the case of devices with bars, the more forward the joints are and the shorter the bars are, the greater the protrusion of the mandible at the analyzed points. In the case of devices with fins or cams, the behavior of the device depends on the fin or cam profile.

An important aspect to consider when studying the kinematic behavior of the mandible when using a MAD is that the mandible is a body that moves with a combined translational and rotational movement. Therefore, from a mechanical perspective, we cannot speak of its absolute protrusion or retrusion, but rather of the advance or retreat of a point on the mandible. Depending on the analyzed anatomical point, we can find one kind of behavior or another. Traditionally, the tip of the lower incisor has been considered to establish the initial advancement of the device with the mouth closed (SP). Therefore, it seems interesting to study whether the advancement of the mandible, when opening the mouth, increases or decreases with respect to the starting position by studying the movement of this point.

However, there is another area of the mandible whose position is related to the opening or collapse of the upper airway that, in our opinion, should be considered when studying the kinematic behavior of a MAD. The main upper airway dilator muscles are the nasal wing dilators, the genioglossus, the geniohyoid, and the posterior cricoarytenoid. The geniohyoid muscle extends from the hyoid to the symphysis of the chin, where the apophysis geni is located. This muscle is important for the opening of the airway, so its shortening or lengthening due to the action of a mandibular advancement device may influence its efficacy. For this reason, the behavior of all the above devices was also studied by analyzing the trajectory of the apophysis geni when opening the mouth. To this end, this point was located in all patients and its Posselt's diagram and its trajectory when opening the mouth were generated, as mentioned in the methodology section.

MADs work by repositioning the mandible in a new vertical and protrusive position and maintaining this new position during sleep (4). Therefore, in this work, we have analyzed

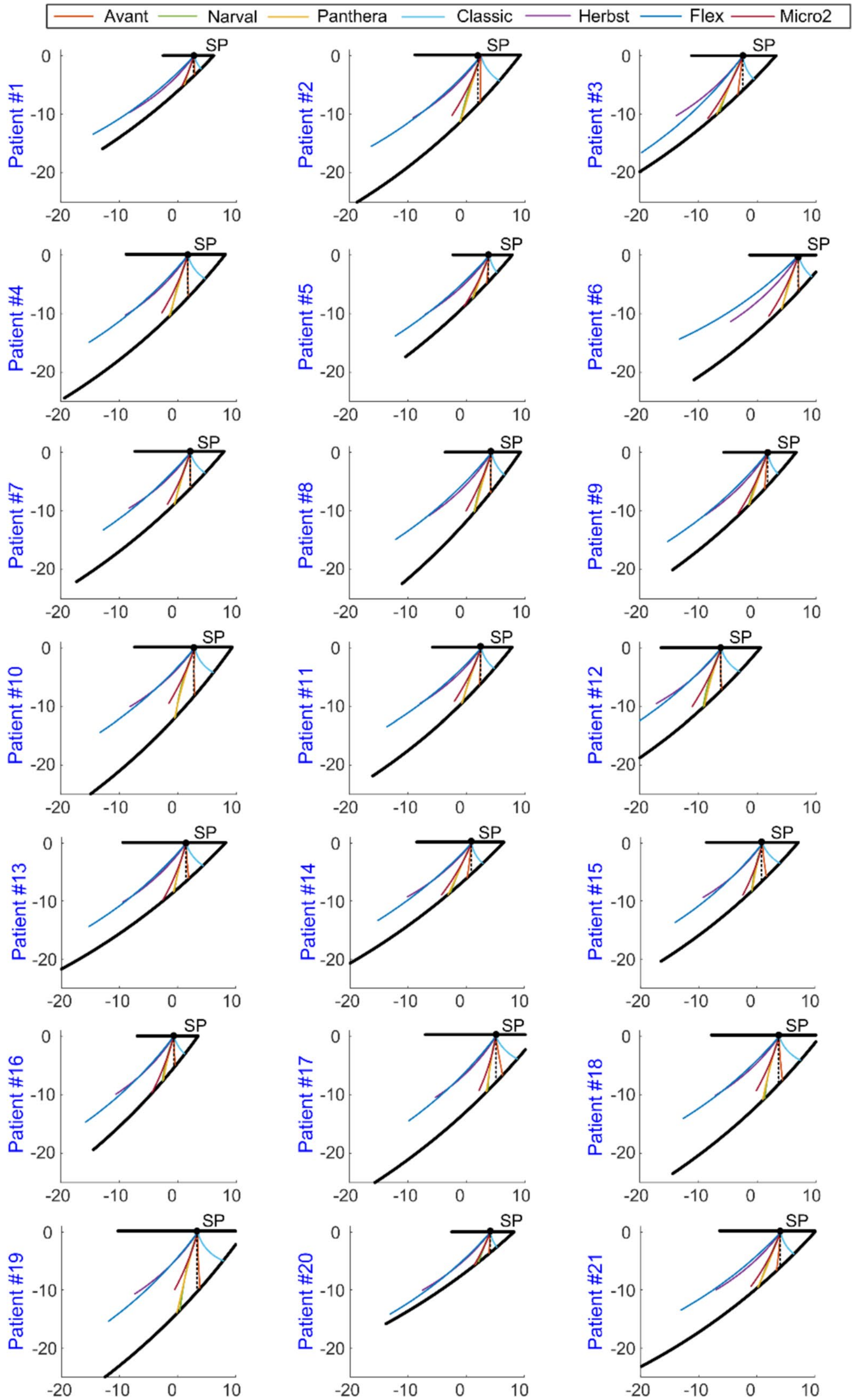

Fig. 7 Representation of the superior and anterior borders of the apophysis geni movement and its trajectory when opening the mouth with each of the devices for all patients

Table 3 Apophysis geni results for the bar-coupled devices

		Classic			Avant			Narval			Panthera			Herbst		
Nr	TA	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	7	2.2	1.2	P	3.2	0.1	P	4.9	−1.7	R	4.9	−1.6	R	9.6	−10.2	R
2	14	4.3	3.1	P	7.9	−0.2	R	11.3	−3.6	R	11.2	−3.6	R	10.6	−11.6	R
3	13	4.0	1.9	P	6.6	−0.9	R	9.4	−3.9	R	10.0	−4.5	R	10.2	−11.4	R
4	14	4.0	2.9	P	7.1	0.0	R-P	10.2	−2.9	R	10.4	−3.2	R	10.2	−10.6	R
5	9	2.9	1.3	P	4.7	−0.5	P	7.4	−2.9	R	7.2	−2.7	R	10.1	−10.9	R
6	11	3.7	2.2	P	6.1	−0.0	R	9.0	−2.8	R	9.1	−2.9	R	11.3	−11.6	R
7	13	3.5	2.5	P	6.0	0.1	R-P	8.7	−2.6	R	8.8	−2.7	R	9.5	−10.4	R
8	11	3.8	2.1	P	6.8	−0.1	R	10.1	−3.0	R	10.0	−2.9	R	10.8	−10.6	R
9	11	3.6	1.7	P	6.2	−0.5	R	9.0	−3.3	R	8.9	−3.1	R	10.7	−10.7	R
10	14	4.2	3.2	P	8.0	−0.0	R	11.7	−3.3	R	12.0	−3.4	R	10.0	−11.0	R
11	12	3.5	2.2	P	6.3	−0.3	R	9.3	−3.2	R	9.5	−3.3	R	9.5	−10.4	R
12	13.5	4.0	3.1	P	7.0	0.1	R-P	10.1	−3.1	R	9.9	−2.9	R	9.5	−11.1	R
13	14.5	3.9	2.9	P	6.0	0.4	P	8.2	−2.0	R	8.4	−2.2	R	10.2	−10.9	R
14	13	3.5	1.9	P	5.9	−0.8	R	8.4	−3.6	R	8.8	−4.0	R	9.2	−11.0	R
15	13	3.4	3.0	P	5.7	0.7	P	8.2	−1.8	R	8.1	−1.8	R	9.3	−10.2	R
16	9	3.0	1.8	P	5.0	0.3	P	7.7	−2.0	R	7.5	−1.8	R	9.9	−9.9	R
17	14.5	3.9	3.6	P	6.6	1.1	P	9.3	−1.4	R	9.4	−1.6	R	10.4	−10.3	R
18	15	4.1	3.6	P	7.5	0.5	P	10.6	−2.5	R	10.8	−2.8	R	10.1	−10.9	R
19	18	4.9	4.4	P	9.6	0.3	R-P	13.4	−3.1	R	13.9	−3.6	R	10.7	−10.8	R
20	9	2.5	1.1	P	3.7	−0.2	R	5.0	−2.0	R	5.6	−2.6	R	10.0	−11.7	R
21	14	3.7	2.3	P	6.6	−0.7	R	9.3	−3.8	R	9.4	−3.9	R	9.9	−11.1	R

TA total advancement [mm], ***A*** opening [mm], ***B*** deviation with respect to the vertical [mm], ***C*** type of curve (Protrusive, Retrusive, Retrusive–Protrusive)

Table 4 Results at the apophysis geni for the SomnoDent Flex and micro2 devices

		SomnoDent Flex			Micro2		
Nr	TA	A	B	C	A	B	C
1	7	13.4	−17.2	R	5.1	−2.1	R
2	14	15.5	−18.7	R	10.2	−5.0	R
3	13	16.5	−17.3	R	10.7	−6.0	R
4	14	14.9	−16.8	R	9.8	−4.4	R
5	9	13.7	−16.0	R	8.7	−4.3	R
6	11	14.3	−20.3	R	10.3	−5.1	R
7	13	13.2	−14.8	R	8.8	−3.9	R
8	11	14.8	−16.3	R	10.0	−4.4	R
9	11	15.2	−17.1	R	10.5	−5.1	R
10	14	14.4	−16.1	R	9.5	−4.4	R
11	12	13.4	−16.1	R	9.1	−4.6	R
12	13.5	15.1	−18.1	R	10.0	−5.0	R
13	14.5	14.4	−16.7	R	9.8	−4.0	R
14	13	13.3	−16.1	R	8.9	−5.2	R
15	13	13.7	−15.0	R	8.9	−3.4	R
16	9	14.7	−15.0	R	9.6	−3.7	R
17	14.5	14.4	−14.8	R	9.2	−2.8	R
18	15	14.1	−16.4	R	9.3	−3.9	R
19	18	15.4	−15.4	R	9.9	−4.0	R
20	9	14.1	−17.2	R	5.6	−2.8	R
21	14	13.4	−17.2	R	9.3	-5.1	R

TA total advancement [mm], *A* opening [mm], *B* deviation with respect to the vertical [mm], C type of curve (Protrusive, Retrusive, Retrusive–Protrusive)

the mandibular kinematics by studying the behavior of two different points: the lower incisor edge and the apophysis geni. These two points, in different areas of the mandible, describe different trajectories as demonstrated in this study. This is in accordance with the work by Garcia et al [13], in which the difference in the movement patterns of these two points was proved.

By analyzing the results of Tables 1, 3 and Figs. 6 and 7 for the devices with bars, it is observed that the greater the protrusion measured with the George gauge, the greater the advancement when opening the mouth wearing the device. On the other hand, it is interesting to compare the difference in the advancement produced by the same device in those patients who have a similar total advancement, but have a different facial biotype. This is the case of patients #2 and #3 or #8 and #9. In both cases, it can be seen that the upper borders of Posselt's diagrams are very similar, but the inclination of the anterior borders is more pronounced in patients #3 and #9 (dolichofacial pattern). Looking at the values in the table for these two patients, it can be seen that the devices produce less protrusion than in patients #2 and #8 (brachyfacial pattern). These results suggest that the facial biotype of the patient influences the behavior of the devices, with worse behavior in dolichofacial patients due to a greater inclination of the anterior border of their Posselt diagrams. In their study about the influence of the facial biotype on the effectiveness of mandibular advancement devices, Camañes et al [30] concluded that in patients with hyperdivergent facial biotypes (dolichofacial), treatment with MAD devices was less effective than in hypodivergent patients (brachyfacial).

In this study, it is observed that all the devices produce less advancement in the apophysis geni, with the Classic device being the only one that maintains a protrusive curve for all patients at this point. Fig. 8 shows a box plot of the ratio between the advancement when wearing the device (deviation) and the total advancement measured with the George Gauge, where the center mark in each box represents the median and the lower and upper ends of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points, which are considered outliers. These outliers are individually represented by the + symbol. In the figure, the area corresponding to forward values of the analyzed point is colored in green and the area of backward values is colored in red. It can be seen that, for all the devices, the advancement measured in the apophysis geni is lower than the one measured in the lower incisor. The behavior of all the devices with fins has retrusive behavior, both in the incisor and in the apophysis geni, being greater in the latter.

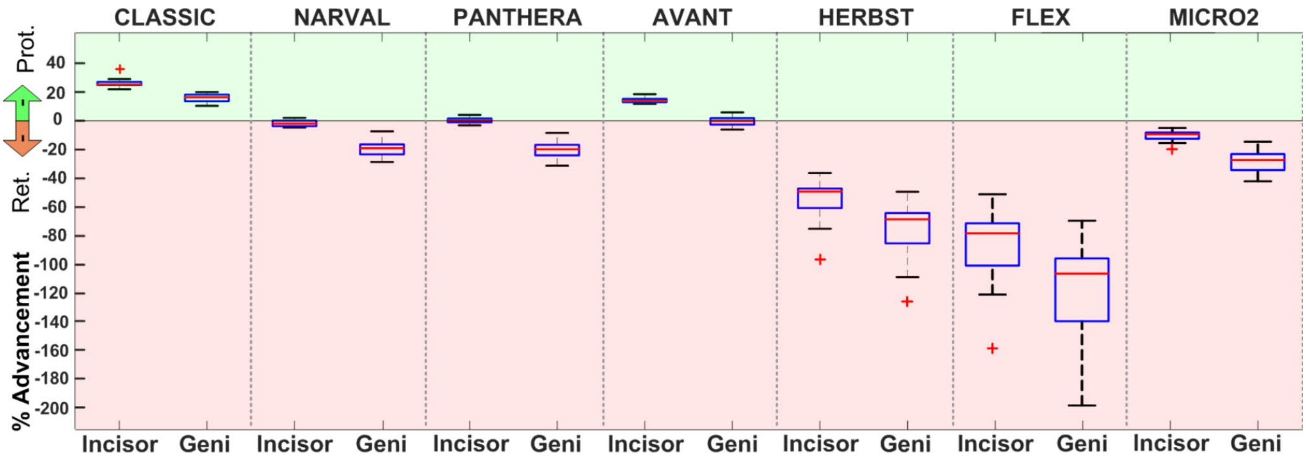

Fig. 8 Box plot of the incisor and apophysis geni advancement ratio (deviation/total advancement) when opening the mouth for all devices

The presence of data points far from the median in the box plots reflects genuine inter-individual variability in the interaction between device design and craniofacial morphology. Devices that cause significant mandibular retrusion when opening the mouth (such as Herbst and Flex) result in greater variation in the advancement ratio among patients with low total advancement values.

According to the movement induced in the jaw, the devices could be classified into three groups: one group gives a higher level of advancement when patients open their mouth during sleep, another group maintains the initial level of advancement and a third group, in which mouth opening leads to a loss of the initial advancement level. The first two groups consist of bar devices while the third group consists of one telescopic bar device and two fin devices. All the bar devices limit mouth opening naturally in all patients due to the path of the incisor reaching the anterior border of Posselt's envelope of motion, not allowing patients to open their mouth any further. Among the devices with bars, the Classic device has a considerably shorter bar than the others, which causes the incisor to describe a trajectory with a smaller radius of curvature. This limits mouth opening more than in the rest of the tested devices. The trajectory of the incisor in the devices with longer bars (Narval and Panthera) has a larger radius of curvature, delaying the contact with the anterior border of Posselt's diagram and, consequently, allowing greater mouth opening. When patients open their mouth with a MAD of the third group, the incisor undergoes a retrusion, moving away from the anterior border of Posselt's diagram, so in most patients, the device does not restrict mouth opening.

Considering that the main objective of a MAD is to reposition the mandible in a forward position that keeps the upper airway open during sleep, retrusion of the mandible when opening the mouth is undesirable behavior of the device. For this reason, it is common for elastic bands to be used to limit the mouth opening of devices, particularly those of the third group. Several studies compare the performance of a SomnoDent Flex device with and without restriction of mouth opening, concluding that the effectiveness of the device, when mouth opening is limited, is greater than when the device does not have this limitation [31, 32].

MADs are designed for an initial incisor advancement (SP) that remains the same in monoblocs, whereas in biblocs, it may vary when opening the mouth. In this regard, some studies have compared monobloc devices with different bibloc devices. Lee et al. [33] compared the effectiveness of a monobloc device with a finned bibloc device with a similar design to the Micro2 device. The work concluded that the monobloc device presented a higher effectiveness. On the other hand, Bloch et al. [34] compared the effectiveness of a Herbst device and a monobloc device, concluding that the latter showed a higher effectiveness. In the same line, Ishiyama et al. [35] carried out a systematic search and meta-analysis, concluding that monobloc devices are more effective than bibloc devices. In the studies included in this meta-analysis, more than two-thirds of the patients were treated with Herbst or similar devices. As it has been proved in this work, the bibloc devices used in the aforementioned comparative studies produce a retrusion of the mandible when opening the mouth (subsequently decreasing their effectiveness. On the other hand, there are studies that do not find a decisive difference between monobloc and bibloc devices. In this regard, Isacsson et al. [36] compared a Narval device with a monobloc device, concluding that their effectiveness was equivalent. This result may be due to the fact that, as shown in Fig. 8, the Narval device has adequate behavior when opening the mouth, maintaining an incisor advancement close to the SP. Therefore, general conclusions can be drawn for monobloc devices, but not for bibloc MADs, as each MAD works differently.

In short, the results of this study indicate that the behavior of each analyzed MAD is different when opening the mouth, depending on the coupling system between the splints and the facial biotype of each patient. Therefore, it is not possible to reach general conclusions about the effectiveness of bibloc MADs by analyzing any device. Rather, the results obtained are for a specific MAD and may be different for another MAD model. To ensure adequate performance of a MAD in any patient, it would be necessary to make a customized device design considering the patient's morphology and the desired trajectory for the considered point of the mandible when opening the mouth: the incisor or the apophysis geni.

To the best of our knowledge, at present, the only device that is designed following these premises is a device with fins called NOA [28]. In this device, the design of the cam profile that controls the coupling between the splints is optimized for each patient, based on the desired trajectory of the incisor. The NOA device has not been included in this study as there is no need to test the device to know the trajectory of the incisor in a patient with a given morphology, since the cam is designed from these data. This was demonstrated in the study of different devices performed with infrared cameras by Cabrera et al [26].

This work has several limitations. A virtual mandibular advancement model is utilized, which does not reproduce the dynamic neuromuscular and tissue level interactions present during sleep. The study was initiated at a fixed 60 % mandibular advancement (≈5 mm opening) based on consensus guidelines, precluding exploration of individualized titration curves that could reveal lower or higher optimal advancements for subsets of patients. The sample size was limited to 21 patients with highly variable morphology. Total mandibular advancement, as measured using the George gauge, ranged from 7 to 18 mm and the ML_1 distance, measured from the center of the condyle to the tip of the lower incisor, ranged from 87.8 to 112.5 mm. The sample was restricted to dentate individuals with full natural dentition, limiting statistical power and the applicability of findings to edentulous or partially dentate populations who commonly require oral appliance therapy. These limitations suggest that the reported kinematic findings should be interpreted as preliminary, and that further in vivo studies with larger, more diverse samples and titration-based designs are necessary to confirm clinical relevance.

To our knowledge, this is the first time a kinematic analysis has been conducted of how different devices perform in different patients. The main conclusions of this work are the following:

- All MADs maintain the jaw in an advanced position with the mouth closed, but when the mouth is opened, some devices lose advancement to a greater or lesser degree depending on the patient's morphology.
- When opening the mouth, MADs using a coupling system based on fins (SomnoDent Flex and Micro2) show worse behavior than those using bars in all patients in the study.
- Mandibular advancement devices based on bars show better behavior in all patients the shorter the bars are and the more advanced their articulated joint in the maxilla is.
- To verify the effectiveness of treatment based on MADs, the MAD design should not only use an adequate coupling system between the splints, but should also be customized for each patient, considering their facial biotype and the way their jaw moves when opening the mouth.
- To avoid disparity in the results of studies on the performance of mandibular advancement devices, it is important to verify that the MAD used maintains the advancement of the mandible when opening the mouth.
- The prescription of the starting point when designing a MAD is based on the position of the incisor. However, the position of the apophysis geni is directly related to the opening of the upper airway and should be taken into account, both when prescribing the initial advancement of the mandible and when studying the behavior of the MAD when opening the mouth.

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Declarations

Competing interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethics approval Ethics approval was obtained from the Universidad Católica de Murcia research ethics board (TC/14-24).

Informed consent Written consent to participate was obtained from every patient whose data were used for this study in accordance with the Declaration of Helsinki and its later amendments.

Clinical Trial Number Not applicable.

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