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Defining Fulcrums for Craniofacial Structures with Midfacial Skeletal Expander (MSE) Treatment and Applying Novel Angular Measurement System for Accurate Assessments

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Abstract

Objective: The aim is to present a novel angular measurement system that can accurately represent the morphological changes after midfacial skeletal expander, having as a reference the precise localization of the rotational fulcrum of the zygomaticomaxillary complex in the coronal plane.

Materials and Methods: Two transverse deficient maxillary cases, 20 years old male and 18 years old female treated with MSE appliance are presented. Pretreatment and post-expansion CBCT records were superimposed and compared. After localizing the rotational fulcrum of the zygomaticomaxillary complex, a novel angular measurement method is presented and compared with a conventional linear method to assess midfacial skeletal expansion outcomes.

Results: For the male case, linear measurements showed 62.7% and 64.33% of skeletal expansion, 12.06% and 7.98% of alveolar bone bending, and 25.24% and 27.69% of dental tipping for right and left side. However, angular measurements accounted for 100% skeletal expansion and 0% of alveolar bone bending and dental tipping in both sides. For the female case, linear measurements suggested 47.79% and 51.7% of skeletal expansion, 10.91% and 20.47% of alveolar bone bending, and 41.6% and 27.83% of dental tipping for right and left side. Angular measurements represented 89.96% and 84% of skeletal expansion, 0% alveolar bone bending and 13.04% and 16% of dental tipping for right and left side.

Conclusion: The rotational fulcrum was located around the most external and inferior point of the zygomatic process of the frontal bone. Traditional linear system could underestimate orthopedic effects and overestimate dentoalveolar side effects. Angular measurements should be preferred.

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Introduction

Rapid Palatal Expansion (RPE) was first described by E.C. Angell in 1860 [1]. Since then, many types of RPE appliances have been developed [2-4] with different rates of expansion, but the principles are essentially the same [5]. Palatal expanders separate the midpalatal suture, leading to skeletal orthopedic expansion [6]. RPE also opens the circum-maxillary sutural systems depending on their anatomic location and degree of interdigitation [7,8].

Because conventional RPE appliances by design transmit the expansion forces through the teeth, alveolar bone bending and dental tipping are inevitable, particularly in older patients [9,10]. To ensure expansion of the basal bone without surgical intervention while attempting to minimize dental side effects, micro-implants have been utilized in conjunction with RPE devices, known as Microimplant-Assisted Rapid Palatal Expanders (MARPE) [11-14].

Although MARPE appliances have been designed to enhance the orthopedic effect of maxillary expansion, dental tipping and alveolar bone bending has been reported in previous studies from RPE/MARPE appliances [9,10,13-16]. Additionally, past studies have relied solely on linear measurements with no consideration to the rotational nature of the maxillary expansion [17].

There is no consensus regarding the fulcrum anatomic location of the maxillary bone during maxillary expansion. Some studies have reported this center of rotation to be localized at the frontomaxillary suture [6,18-20] while others point it close to the superior orbital fissure [21,22]. A recent Cone Beam Computed Tomography (CBCT) study with Midfacial Skeletal Expander (MSE) has established that the zygomatic bone and maxilla move as a unit consistently, with its fulcrum slightly above the frontozygomatic suture in the coronal plane [17]. Since the expansion with MSE is Archial in nature and the fulcrum location can be defined, perhaps an angular measurement system should be used to assess the expansion pattern of this appliance.

This methodological paper aims to present a novel angular measurement system that can accurately represent the MSE expansion outcomes having as a reference the precise localization of the rotational fulcrum of the zygomaticomaxillary complex in the coronal plane.

Material and Methods

Institutional review board approval (IRB number 16-001662) was granted by the University of California, Los Angeles (UCLA). Two cases are presented, consisting of pre-treatment and post-expansion CBCT records of a 20 years old male and an 18 years old female, who were treated with MSE (Biomaterials Korea, Seoul, Korea) appliance. The patients were diagnosed with maxillary transverse deficit and posterior crossbite, without craniofacial irregularity nor previous orthodontic treatment. Treatment was performed at the Section of Orthodontics, UCLA School of Dentistry, under supervision of one clinician.

Figure 1 describes the method used to assess the discrepancy between the maxillary and mandibular width. Maxillary bone width is represented by the distance between the right and left most concave points lying on the maxillary vestibule at the level of the mesiobuccal cusp of first molars. Mandibular bone width is defined as the distance between the right and left gingiva tissue projected at the level of first molar’s furcation. This anatomic structure corresponds with the center of rotation for the lower fist molar and provides an estimation of the amount of bucco-lingual decompensation needed. In the past, WALA ridge [23] was used to determine mandibular width. However, it is difficult to be defined in cases with excessive lingual inclination, without prominent buccal ridge. The difference between the mandibular and maxillary bone widths provides a guideline for the required maxillary skeletal expansion.

MSE was indicated in lieu of traditional tooth-borne expanders, based on patients’ maturity and cervical vertebral maturation stage higher than CS4 [24]. An MSE device (Figure 2) consists of a jackscrew unit with four holes, housing the palatal micro-implants which engage the palatal bone bicortically. Additionally, two supporting arms extend from the jackscrew and are soldered to the molar bands. The rate of expansion was 2 turns per day (0.25 mm per turn) until a significant diastema of 2 mm to 3 mm. appeared; then the rate changed to 1 turn per day. MSE activation was stopped when the maxillary skeletal width, defined in Figure 1, matched or was greater than the mandibular width. The MSE was maintained in place with no further activation for at least 6 months during the restructuring of the suture.

The CBCT scans were taken before expansion and within 3 weeks after completion of the expansion. The time between the scans was 3 months for both patients. In order to assess the outcomes induced purely by MSE, the post-expansion scans were obtained before patient received any other orthodontic appliances. A CBCT scanner (5G; NewTom, Verona, Italy) was used, with an 18 cm × 16 cm field of view, 14-bit gray scale, and a standard voxel size of 0.3 mm. Configuration of the CBCT included scan time of 18 sec (3.6 sec emission time), with 110 kV. An automated exposure control system was used to detect the patient's anatomic density, to properly adjust the milliamperes. On demand 3D (Cybermed, Daejeon, Korea) software was used for superimposing the pre-expansion and post-expansion CBCT images [25].

Localization of fulcrum

After superimposition of CBCT images, the following steps were taken to localize the fulcrum of the zygomaticomaxillary complex. The maxillary sagittal plane was identified [8], passing through the anterior nasal spine, posterior nasal spine, and nasion on the pre-expansion CBCT image (Figure 3). Then the coronal zygomatic section (Figure 4) was selected. This section passes through the uppermost point of the frontozygomatic sutures and the lowermost point of the zygomaticomaxillary sutures. The previous study by Cantarella [17] indicated that fulcrum is near the external surface of the frontozygomatic suture because the suture is the weakest point during the Archial movement of midfacial structure. The most external and inferior points of the zygomatic processes of the frontal bones were chosen as initial reference points. The interfrontal distance between these two reference points were measured on both pre- and post-expansion CBCT images (Figure 5). If these two measurements were different, the correct fulcrum points must be more superiorly located. A parallel line slightly above the initial interfrontal line was used to identify the true fulcrums by incrementally moving this line upwards until both pre- and post-expansion distances were equal. This newly established line with no width changes was named the modified interfrontal distance, and the most external points of this line were denoted as the right and left rotational fulcrum respectively (Case 1, (Figure 5A)). If the initial interfrontal distances (pre- and post-expansion) were the same, the most external points of this

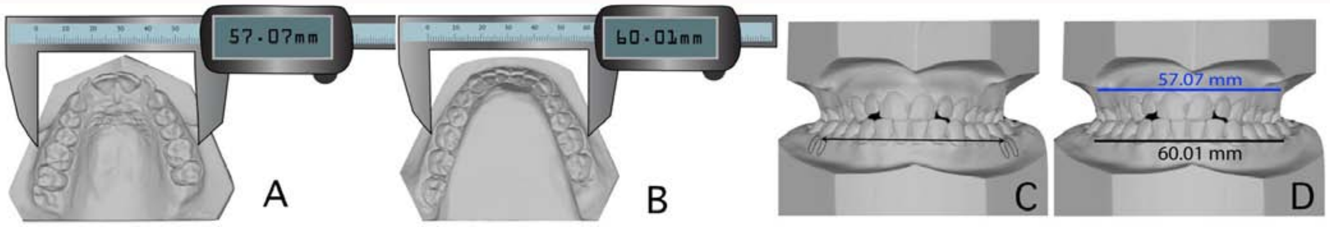

Figure 1: Method used to diagnose transverse maxillary skeletal deficiency. Measurement of A) maxillary and B) mandibular widths with a digital caliper; C) Mandibular basal bone width is defined as the distance between the right and left gingiva tissue projected at the level of first mandibular molar’s furcation; D) frontal view of the relationship between maxillary (blue) and mandibular (black) widths. In this patient, maxillary width is 57.07 mm, and mandibular width is 60.01 mm, for a maxillary transverse deficiency of 2.94 mm.

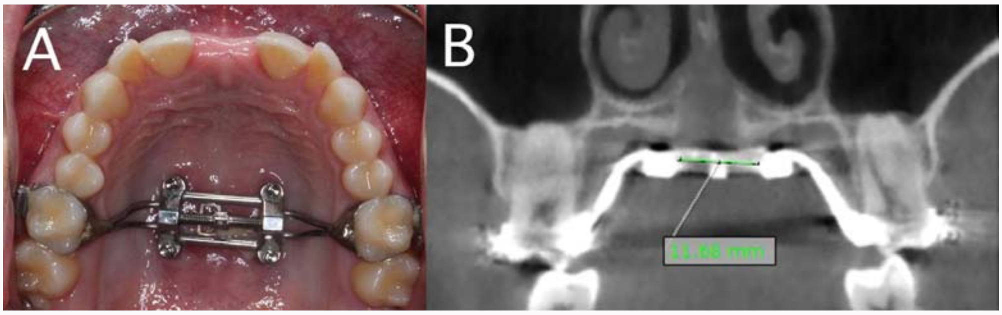

Figure 2: Maxillary skeletal expander: A) intraoral occlusal view; B) CBCT coronal section. The opening of the mid-palatal suture can also be appreciated.

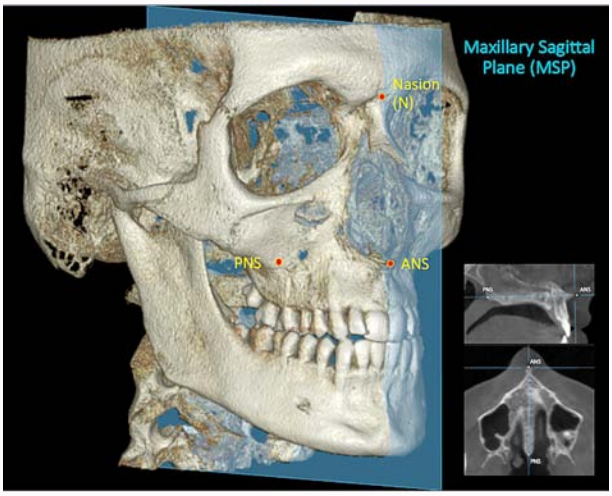

Figure 3: 3D Reconstruction with the Maxillary Sagittal Plane (MSP) passing through Anterior Nasal Spine (ANS), Posterior Nasal Spine (PNS) and Nasion (N) on the pre-expansion CBCT.

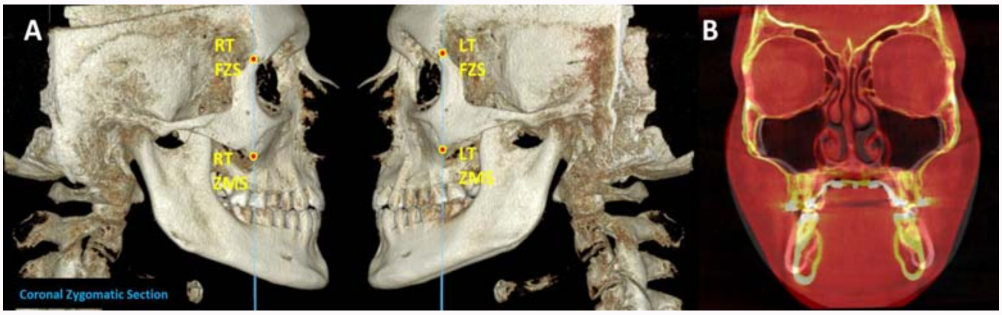

Figure 4: A) Coronal zygomatic section in blue passing through the right and left Frontozygomatic Sutures (FZS) and Zygomaticomaxillary Sutures (ZMS); B) Pre-treatment and post-treatment superimposed image of an MSE patient in the coronal zygomatic section.

line can be denoted as right and left rotational fulcrum points. To verify this, a parallel line slightly below the initial interfrontal line was used to confirm that the post-expansion distances were greater than the pre-expansion. In this situation, the modified interfrontal line is the same as initial interfrontal line (Case 2, (Figure 5B)). To further verify the true center of rotation, two different landmarks in the zygomatic bone were chosen and the angular displacement was measured around this proposed fulcrum point. One landmark was the zygomaticomaxillary suture and the other landmark was easily definable corresponding landmarks within the zygomatic bone in both pre- and post-expansion CBCT (Figure 6). The angles formed between the modified interfrontal line and the line connecting the proposed fulcrum to two chosen landmarks were measured. The changes in pre- and post-expansion values were identical for the two measurements within each zygoma in all cases, confirming the accuracy of the fulcrum locations (Figure 6).

Novel angular measurement system

From the rotational fulcrum, three angular measurements were selected to differentiate the skeletal, alveolar and dental components of the expansion. The following angular measurements were selected: The Frontozygomatic Angle (FZA) is an angle between the interfrontal line and the line extending from fulcrum to the most external point of the zygomaticomaxillary suture, the Fronto-Alveolar Angle (FAA) is an angle between the interfrontal line and the line extending from fulcrum to the alveolar bone surface at the level of distobuccal root tip of the upper first molars, and the Fronto-Dental Angle (FDA) is an angle between the interfrontal line and

Figure 5: Reference line to determine rotational fulcrum. A) Interfrontal Distance (IFD) and Modified Interfrontal Distance (MIFD) to determine the rotational fulcrum in the male patient; x: Distance between IFD and MIFD. B) Interfrontal Distance (IFD) to determine the rotational fulcrum in the female patient.

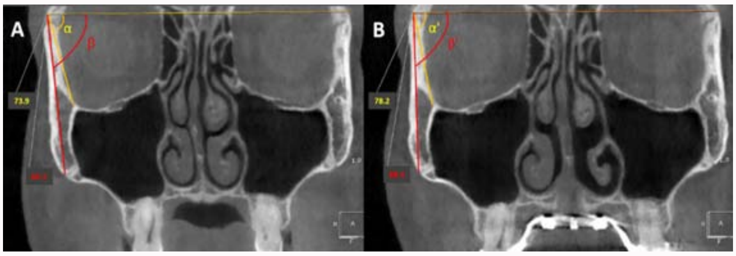

Figure 6: According to the Reuleaux technique, at least two corresponding landmarks must show uniform displacement around a single point, to be able to pinpoint a center of rotation. A) Pre-expansion measurements. B) Post-expansion measurements. By subtracting the pre-expansion values from the post expansion values (α'-α = β'-β), we have the same 4.3° of difference.

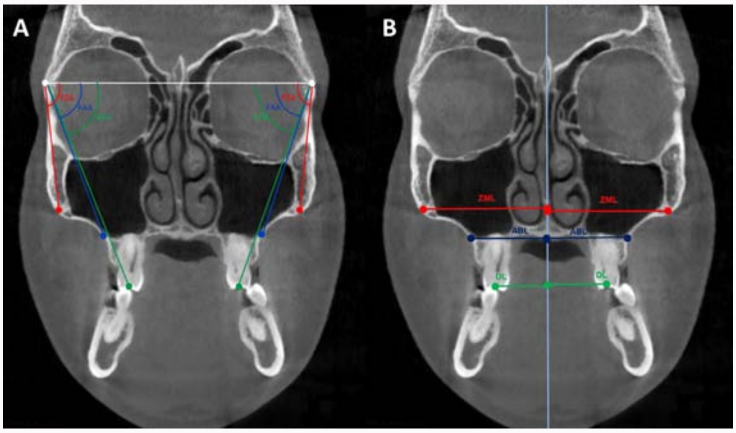

Figure 7: Measurement systems in the coronal zygomatic section. A) Angular measurement system: Frontozygomatic Angle (FZA), Fronto Alveolar Angle (FAA), and Fronto Dental Angle (FDA); B) Linear measurement system: Zygomaticomaxillary Line (ZML), Alveolar Bone Line (ABL), and Dental Line (DL). Light blue line represents the maxillary sagittal plane.

the line extending from fulcrum to the occlusal point located at the central groove of the upper first molar (Figure 7). For FAA, a line parallel to the interfrontal was moved down until it contacted the tip of the root, and the alveolar surface that intersects the line was chosen. These three different angles were measured on both sides, and the pretreatment value was subtracted from the post-expansion value in order to determine the treatment change for each component. The FZA changes correspond to the zygomaticomaxillary expansion, a true skeletal expansion (FZA changes); the FAA changes correspond to the sum of the skeletal expansion (FZA change) and the alveolar bone bending (FAA changes-FZA changes); and the FDA changes correspond to the sum of the skeletal expansion (FZA changes), alveolar bone bending (FAA changes-FZA changes) and the dental tipping (FDA changes-FAA changes).

With the same coronal zygomatic section, a set of traditional linear distance measurements were employed (Figure 8). The Zygomaticomaxillary Line (ZML), the Alveolar Bone Line (ABL), and the Dental Line (DL) are perpendicular lines connecting the three landmarks used for the above angular measurements to the intersecting points on the maxillary sagittal plane. The changes in the three sets of linear measurements, before and after the MSE treatment, were calculated for both sides in order to determine the treatment change of each component. The ZML changes describes the Zygomaticomaxillary skeletal changes (ZML changes); the ABL changes as the sum of the skeletal change (ZML change) and the alveolar bone bending (ZML changes-ABL changes); and the DL changes as the sum of the skeletal change (ZML change), alveolar bone bending (ZML changes-ABL changes) and the dental tipping (DL changes-ABL changes).

Statistical analysis

All measurements were obtained three times by 2 raters, to assess method reliability. Measurements were then repeated after 2 weeks by the same operators. Additionally, to compare linear and angular measurements for the two selected cases, both linear and angular measurements of the three components were transformed to relative percentages from the total expansion, the fronto-dental changes.

Results

The amounts of activation of the MSE expansion jackscrew were 11.5 for the male patient and 7.5 for the female patient. The duration of maxillary expansion was 23 and 15 days respectively.

For the male case selected, the treatment change with linear measurements at the zygomaticomaxillary level was 4 mm and 3.95 mm (right and left sides), at the alveolar bone level was 0.77 mm and 0.49 mm. (right and left sides), and at the dental level was 1.61 mm and 1.7 mm. (right and left sides). These values suggest 62.7% and 64.33% (right and left sides) skeletal expansion, 12.06% and 7.98% (right and left sides) alveolar bone bending, and 25.24% and 27.69% (right and left sides) dental tipping. In contrast, the treatment change with angular measurements at the zygomaticomaxillary level was 4.3º and 4.4º (right and left sides), at the alveolar bone level was 0º (both right and left sides), and at the dental level was 0º (both right and left sides). These values represent 100% skeletal expansion for the right and left sides, 0% alveolar bone bending and dental tipping for the right and left sides (Table 1).

For the female case selected, the treatment change with linear measurements at the zygomaticomaxillary level was 1.61 mm and 1.97 mm (right and left sides), at the alveolar bone level was 0.37 mm and 0.78 mm. (right and left sides), and at the dental level was 1.41 mm and 1.06 mm. (right and left sides). These values suggest 47.79% and 51.7% (right and left sides) skeletal expansion, 10.91% and 20.47% (right and left sides) alveolar bone bending, and 41.6% and 27.83% (right and left sides) dental tipping. In contrast, the treatment change with angular measurements at the zygomaticomaxillary level was 2º and 2.1º (right and left sides), at the alveolar bone level was 0º (both right and left sides), and at the dental level was 0.3º and 0.4º (both right and left sides). These values represent 89.96% and 84% of skeletal expansion for the right and left sides, 0% alveolar bone bending for right and left sides and dental tipping of 13.04% and 16% for the right and left sides respectively (Table 2). For the considered parameters, the ICC value was 0.95.

Discussion

Each expansion device produces expansion force directed at different parts of craniofacial structure, depending on its design and the means of anchorage. The expansion pattern can greatly vary from one appliance to another. MacGinnis [26] illustrated the difference between MSE and Hyrax using FEM simulation. A study on FEM located the fulcrum around the upper border of the orbit [19], while others stated that is placed near the frontomaxillary suture [18,20,26]. Other studies on FEM mention that the maxillary center of rotation is located near the superior orbital fissure [22,27]; that in agreement with the results of Gardner and Kronman [28] in a study with rhesus monkeys. Even micro-implant supported expanders exhibit various pattern of expansion [11,17], based on the anchor placement, depth of implant engagement, expansion protocol, etc. [11,28]. The MSE has a unique feature, promoting skeletal movement in Archial manner, around the fulcrum located near the frontozygomatic sutures. Cantarella [17] has illustrated this effect but the precise location of the fulcrum was not clearly defined, only indicating that it is near the frontozygomatic suture. In the current study, additional steps were taken to further define the true points of rotation. The interfrontal distance which connects two fulcrums should not change with the expansion. In addition, the interfrontal distances connecting the points above the fulcrum should not change but the distance

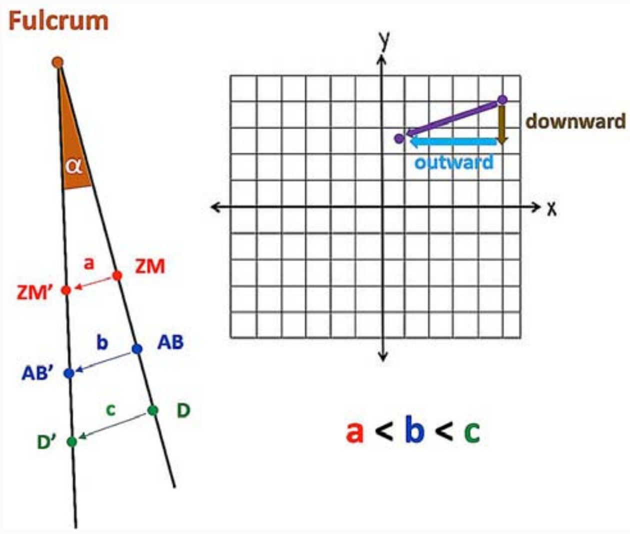

Figure 8: Schematic illustration showing that, for the same angle, points closer to the fulcrum undergo a shorter linear displacement than points farther from the fulcrum. Initial points while moving along the fulcrum are displaced in a downward and outward direction.
ZM: Pre-expansion zygomaticomaxillary point; ZM': Post-expansion zygomaticomaxillary point; AB: Pre-expansion alveolar bone point; AB': Post-expansion alveolar bone point; D: Pre-expansion dental point; D': Post-expansion dental point; a: Linear skeletal distance; b: Linear alveolar bone distance; c: Linear dental distance

Figure 9: A) Pre- and B) post-expansion coronal zygomatic section of the male case.

Figure 10: A) Pre- and B) post-expansion coronal zygomatic section of the female case.

Table 1: Linear and angular measurements for male case.

				Skeletal expansion	Alveolar bone bending	Dental tipping
	Right linear measurements					
Unit	Δa	Δb	Δc	Δa	Δb - Δa	Δc – Δb
mm.	4 mm.	4.77 mm.	6.38 mm.	4	0.77	1.61
%				62.70%	12.06%	25.24%
	Right angular measurements					
	Δa	Δb	Δc	Δa	Δb – Δa	Δc - Δb
mm.	4.3°	4.3°	4.3°	4.3°	0°	0°
%				100%	0%	0%
	Left linear measurements					
	Δa	Δb	Δc	Δa	Δb - Δa	Δc - Δb
mm.	3.95 mm.	4.44 mm.	6.14 mm.	3.95	0.49	1.7
%				64.33%	7.98%	27.69%
	Left angular measurements					
	Δa	Δb	Δc	Δa	Δb - Δa	Δc - Δb
mm.	4.4°	4.4°	4.4°	4.4°	0°	0°
%				100%	0%	0%

Δa: Skeletal expansion; Δb: Skeletal expansion + Alveolar bone bending; Δc: Skeletal expansion + Alveolar bone bending + Dental tipping

connecting the points immediately below the fulcrum should increase with expansion. By applying these concepts, the fulcrum positions were identified. Arbitrarily, the most external and inferior points of the right and left zygomatic processes of the frontal bone were used for initial interfrontal distance measurements. If the distance changed with expansion, the line was moved upward until the distance was stable (Case 1). If this initial interfrontal distance did not change, the line was moved downward and verified that the distance increased below the initial reference points (Case 2). Once these fulcrum points were established, one additional step was taken, in order to ensure that these were truly the points of rotation. According to the Reuleaux technique [29], at least two corresponding landmarks

Table 2: Linear and angular measurements for female case.

				Skeletal expansion	Alveolar bone bending	Dental tipping
	Right linear measurements					
Unit	Δa	Δb	Δc	Δa	Δb - Δa	Δc - Δb
mm.	1.61 mm.	1.98 mm.	3.39 mm.	1.61	0.37	1.41
%				47.49%	10.91%	41.60%
	Right angular measurements					
	Δa	Δb	Δc	Δa	Δb - Δa	Δc - Δb
mm.	2°	2°	2.3°	2°	0°	0.3°
%				86.96%	0%	13.04%
	Left linear measurements					
	Δa	Δb	Δc	Δa	Δb - Δa	Δc - Δb
mm.	1.97 mm.	2.75 mm.	3.81 mm.	1.97	0.78	1.06
%				51.70%	20.47%	27.83%
	Left angular measurements					
	Δa	Δb	Δc	Δa	Δb - Δa	Δc - Δb
mm.	2.1°	2.1°	2.5°	2.1°	0°	0.4°
%				84%	0%	16%

Δa: Skeletal expansion; Δb: Skeletal expansion + Alveolar bone bending; Δc: Skeletal expansion + Alveolar bone bending + Dental tipping

must show uniform displacement around a single point, to be able to pinpoint a center of rotation. The displacement of two separate landmarks within a zygomatic process around the proposed fulcrum were measured, and they showed uniform displacements, indicating the fulcrum position was accurate (Figure 6).

The fulcrum positions for these two individuals were identified by the findings from previous studies of MSE and by applying additional measurements; however, the fulcrum position may vary greatly with other expansion devices because of the design differences described above. Since most of the expansion devices lack fulcrum information, the pattern of expansion was customarily described by linear width changes of various points within the structures. If the skeletal movement was Archial in nature as seen in MSE cases, the differential movements measured by these linear distances introduce inherent error. The linear distance changes were greater for the landmarks further away from the fulcrum, falsely exaggerating the magnitude of alveolar bone bending and dental tipping (Figure 9). This effect was examined by applying both linear measurements often used traditionally and novel angular measurements stemming from the fulcrum points.

Two MSE cases were selected to illustrate the difference between the angular and linear measurements. The first case was a male patient who had received MSE treatment with optimal quality expansion (Figure 9). When the angular measurements were employed (Figure 7A), the results clearly indicated that there was no alveolar bone bending or dental tipping, but the entire movement was a skeletal rotation from the fulcrum, identified from the first part of this study (Table 1). On the other hand, the linear measurements (Figure 7B) yielded different results with exaggeration of the dentoalveolar components: 12% R and 8% L bone bending, and 25% R and 28% L dental tipping (Table 1). Because the movement was in Archial configuration, the structures further away from the fulcrum were displaced more (Figure 8). These discrepancies in linear length change can be misinterpreted as the alveolar bone bending and the dental tipping were significant components of the expansion. However, the angular measurements indicated that the expansion was purely skeletal, with midfacial rotation and with no additional bone bending or dental tipping. With MSE, both zygomatic bone and maxilla were rotating around the fulcrum, without significant bone bending or dental tipping [17]. The MSE is placed at the palatal vault, close to the center of resistance, and the micro-implants were engaged bicortically promoting superior expansion. The MSE produced an orthopedic response, causing the fulcrum to be near the weaker frontozygomatic suture [17]. The best way to differentiate the percentage of skeletal expansion, alveolar bone bending and dental tipping for MSE is to use the angular measurements from this fulcrum. This novel measurement system can eliminate the inherent error associated with the linear distant measurements discussed above.

The second case was a female patient who has a successful split of midpalatal suture but with difficulties, yielding some tipping of the implants during the expansion (Figure 10). Some bone bending and dental tipping was anticipated with this patient, and this case was chosen to prove that the novel angular measurements can illustrate these changes. The angular measurements (Figure 7A) indicated that most of the expansion was skeletal (87% R and 84% L). There was no alveolar bone bending but some dental tipping (13% R and 16% L). As the implants tipped during the expansion, the molars experienced some buccal tipping, but the alveolar process did not move further away from the zygoma as the midfacial complex was rotating from the fulcrum (Table 2). On the other hand, the linear measurements (Figure 7B) yielded very different results with exaggeration of the dentoalveolar components 11% R and 20% L bone bending, and 42% R and 28% L dental tipping (Table 2). These sets of numbers indicate entirely different expansion pattern, emphasizing that linear measurements are severely inaccurate in assessing Archial movement, as seen in MSE.

In the past, many studies [10,13-16,20,30] have evaluated the maxillary expansion outcomes with linear measurements. Assuming that the fulcrums of these changes were above the landmarks they have chosen for the distance measurements, the linear distance changes for the alveolar bending and dental expansion were probably exaggerated, simply by the fact that these landmarks were further away from the fulcrum. If we assume that the skeletal expansion is Archial in nature, the intermolar distance will increase more than the skeletal components, even with pure skeletal rotation. The actual dental tipping may be much less than the reported values. However, the angular measurements can also have inherent errors if they are measured from the wrong fulcrum. The fulcrum location may vary with each appliance, and the origin of the angular measurements must be identified.

Obtaining the accurate measurements differentiating skeletal, dentoalveolar and dental expansion is a difficult task, as illustrated above. Two conditions must be met in order to produce accurate valuation: The identification of the true fulcrum and the designing of the angular measurements from this fulcrum. Each appliance presumably has different fulcrum location, and it is important to identify the accurate position. With MSE, the fulcrum was located near the frontozygomatic suture [17]. In this study, this area was further explored, in order to define the precise fulcrum position, utilizing the superimposed CBCT images, acquired before and after the expansion. Subsequently, the three angular measurements from this fulcrum were used to differentiate skeletal, alveolar and dental components of the expansion. By using these angular measurements radiating from the fulcrum, the above-mentioned problems with linear distance measurements can be eliminated. This new mathematical approach illustrated that commonly used linear analysis may not be the best way to assess the differential components of maxillary expansion.

In this study the precise rotational fulcrum of the zygomaticomaxillary complex after MSE treatment was determined, and a novel angular measurement system that accurately assesses the expansion outcomes has been developed. The results obtain from the cases in this study are not representative for all the MSE cases. These cases were selected to illustrate a novel methodology that can accurately assess expansion of MSE. A further study will be conducted in order to assess the overall impact of MSE treatment, by applying the method developed in this study to all MSE cases. Further studies in defining the fulcrum locations for other expansion appliances would be beneficial in accurately determining the expansion outcomes.

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