Three-dimensional mandibular changes associated with Class II elastics and extractions treatment in adult patients

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Research Article

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Abstract

Background: The application of Class II elastic can induce the rotation of mandible and condylar response. The purpose of this study was to assess the positional and morphological alterations of mandible after orthodontic treatment with Class II elastic by using of 3-dimensional superimposition of pretreatment (T1), posttreatment (T2) and after retention (T3) CBCT data.

Methods: With sequential 3D superimpositions that combined cranial base superimpositions with regional mandibular superimpositions, the virtual reference mandibles were placed to distinguish morphological changes from positional changes. The morphological changes and positional changes of mandibles were measured by comparing multiple combinations of reference and original mandibles respectively, and the corresponding paired t test was performed using SPSS (IBM SPSS version 23).

Results: During orthodontic treatment (T1-T2), the mandibular molars were extruded, and the condyles were revealed apparent adaptive remodeling and upward/backward displacements. The mandible rotated backwardly and drifted backwardly/downwardly. The condylar growth and displacements were significantly different. The condylar growth did not induce isometric displacements and the forward rotation was restricted. Two years after retention (T2-T3), continuous morphological and positional changes occurred. The condylar remodeling and forward/downward displacements induced forward mandibular rotation and neutralized the backward rotation during treatment period (T1-T2). The overall positional changes (T1-T3) were translations with slight rotation. Statistically significant differences were found between the treatment and overall variables regarding the 3D rotation, condylar displacement, Pog displacement. And with the continuous morphological and positional changes, the condyle moved back to the initial position after the retention stage.

Conclusion: the sequential 3D superimposition method can produce the reference mandibles and distinguish the morphological changes from positional alterations. The class II elastics induced mandibular complex changes including condylar adaptive remodeling and 3D rotation and translation. The condyles morphologically adapted to resist the rotation effects of Class II elastic.

Introduction

Class II malocclusion presents a major and common challenge to orthodontists. Class II elastics are frequently undertaken for correcting a Class II malocclusion [1, 2]. In the general opinion, Class II correction with Class II elastics is accomplished by dentoalveolar changes without mandibular (TMJ) growth stimulation [3-6]. Class II elastics are effective in correcting Class II malocclusions, and their effects are mainly dentoalveolar in maxillary incisors, mandibular incisors and molars. It also has been stated that Class II elastics can cause clockwise rotation of the occlusal plane and the mandible due to the extrusion of the mandibular molars and maxillary incisors and change mandibular position[7]. As we know, changes in mandibular position might be expected to produce or be associated with changes in condylar growth and mandibular remodeling [8,9]. The Class II elastic Experimental studies in monkeys
and in rats have shown that condylar modeling could be accomplished with Class II elastics[10,11,12]. The condylar adaptation to the changes of mandibular position may induce secondary mandibular rotation and TMJ remodeling. Considering of the condylar adaptation, the effects of Class II elastic must be complex and long-term.

The complex biomechanism and various effects of class II elastics have interested the orthodontists for a long time [13-16]. In the previous retrospective studies, the researchers have placed a significant amount of emphasis on the dental and skeletal components and facial profile changes after treatment. Previous studies were limited to the two-dimensional (2D) cephalometric device and other technical limitations, the alterations of the tempromandibular joint have always been ignored. In conventional cephalograms, the single components of the TMJ changes are difficult to assess as appropriate TMJ landmarks are difficult to define and the condylar is overlapped by surrounding tissue. The two dimensional nature of lateral cephalograms presents an inherent limitation to the clinician for assessment of TMJ changes.

In recent years, many of the limitations associated with conventional cephalometrics have been overcome by the use of 3-dimensional imaging, Cone-beam computed tomography (CBCT) is becoming widely available as a diagnostic tool in orthodontics [17-20]. Assessment of treatment outcomes by the use of cone beam computed tomography (CBCT) has the potential to unravel the interactions of mandibular components that underpin the response to treatment [21-24]. The three-dimensional (3D) superimposition techniques make the quantitative analysis of mandibular complex possible, and provide new opportunities for orthodontists to understand and distinguish the mandibular positional rotation and morphological remodeling resulting from the growth and/or treatment. Maxillary and Mandibular adaptive and positional changes can be accurately examined and measured relative to the anterior cranial base using these 3D superimposition techniques [25]. Recently, 3D mandibular regional superimposition was shown to be reproducible and accurate [26-29]. With 3D mandibular regional superimpositions the mandibular morphological changes in the condylar region, mandibular surface remodeling, and dentoalveolar alterations can be measured quantitatively. The 3D superimposition techniques make the quantitative analysis of mandibular complex possible, and provide new opportunities for orthodontists to understand and distinguish the 3D mandibular positional rotation and morphological remodeling resulting from the class II treatment.

The object of the present investigation is to study the effects of class II elastic in the mandibular rotation and possible TMJ secondary remodeling which were ignored in previous 2D cephalometric studies. To avoid the interference of normal growth, the study subjects were young adults after growth. In this study, we attempt to introduce a sequential 3D superimposition method to evaluate the long-term effects of class II elastic, with emphasis on 3D mandibular rotation and TMJ secondary remodeling and reveal the secondary orthopedic effects of class II elastic in angle class II division 1 malocclusion.

Material And Methods
Eleven patients (five females, six males, age 19-23 yrs) with Class II, division 1 malocclusion (overjet 5-7mm) and asymptomatic TMJs was recruited for this study. Informed consent was obtained from the subjects, and the experimental protocols were approved by the Research Ethic Committee of Shandong university dental school (The qualifications and experience of the researchers meet the requirements of experiments; the research programs are in line with the scientific and ethical principles; The informed consent is obtained appropriately; Compared with the expected benefit of the research, the risk that the subjects may suffer is negligible). The patients have understand and approved this consent procedure, and provided the permission for our research basing on her CBCT data.

The patients did not accepted extraoral headgear and miniscrew for additional anchorage, intermaxillary class II elastic was applied for subsequent anterior tooth retraction and normalizing the molar relationship. The patients were corrected from Class II occlusal relationship to a normal occlusion with extraction of the maxillary and mandibular first premolars and Class II elastics. The average treatment period and intermaxillary traction period was 2.2 years and 7.5 months.

Images were acquired using the CBCT scanner (KaVo Dental GmbH, Bismarckring, Germany) at a 0.30-voxel resolution with the scanning parameter of 120 kV, 5mA. The scan time was 8.9 seconds, and the slice thickness was 0.4mm. The CBCT datasets were exported in the DICOM (Digital Imaging and Communications in Medicine) format. The CBCT scans were taken at three time points: before (T1), after treatment (T2) and after retention(T3). And the CT iamges were imported in the MIMICS 20.01 for image processing. The procedure of 3D image acquisition and analysis for evaluation is the following.

1. Segmentation and reconstruction

Image segmentation of the anatomic structures of interest and the 3D graphic rendering were done by using the Mimics medical imaging density segmentation software. Various threshold values were selected that would produce as complete structures of the craniofacial complex as possible without too many holes or artifacts. All 3D models of T1,T2 and T3, such as maxillia, mandible, the cranical base and the mandibular chin were reconstructed respectively (Figure.1).

2. Sequential 3D superimposition

2.1 Regional superimposition of T1 and T2 mandibles

After 3D reconstruction, the 3D models of the T1 mandible and chin were exported as standard triangulated language (STL) points for superimposition to T2 mandible. Unlike the remodeling/modeling of condyle and alveolar process, the chin and symphysis regions are stable areas for 3-dimensional mandibular regional superimpositions [26,28].

Superimpositions of the mandibles were performed initially by manual point registration to approximate the surfaces as much as possible. The mandibular surface feature points which were easy to identify on the two mandibles were located for the initially superimposition (Figure.2 a-c). The T1 mandible and chin were registered to the T2 mandibular model grossly. Subsequently, superimposition was refined using the
STL registration method. The transformation matrix of this method registered the stack of slices of the inferior chin STL models on the stack of slices of the mask of the T2 model sequentially (Fig.2 d). These transformations of the 3D models (mandible and chin) were synchronous. After the sequential rigid superimpositions (translation and rotation), the T1 mandible was aligned to T2 mandibular positions. The T1 mandible which was placed at the T2 positions were defined as reference mandible (T1r2). With the identical core position with T2 mandible and the same morphology with T1 mandible, the reference mandible can be used for separating the positional and morphological changes of mandible when they was exported back into T1 project file. After the regional superimposition of T1 and T2 mandibles, the morphological changes between T1 and T2 mandibles can be measured quantitatively. The growth volume at condyles can be separated and quantified after the 3D boolean operation of T1 and T2 mandibular models (subtraction).

The post-treatment 3D models such as cranial base, maxillary, mandible, chin, upper and lower teeth(T2) and the T1r2 reference mandible were exported as STL models for the subsequent registrations. The T2 mandible and chin, T1r2 reference mandible were imported into the T3 project file for mandibular regional superimpositions. The superimposition process was same as T1 and T2 mandibular registration (Fig.3 a-d). The T2 and T1r2 mandibles were aligned to the T3 position and acted as reference mandibles for calculating T3 mandibular position difference with T1 and T2 mandibles. The two mandibles were defined as T2r3 and T1r3 mandibles. After T3 mandibular regional superimposition, all the T3 models and T1r3/T2r3 mandibles were exported out as STL format for follow-up cranial base superimposition in T1 project file.

2.2 Global superimposition on cranial base

In the Mimics, the 3D models derived from T2 and T3 projects were imported into the T1 project file. The T2 models and T1r2 mandible were registered to the T1 structures by using the anterior cranial fossa as the reference (Fig.4 a-d). And the T3 models and T1r3/T2r3 mandibles were aligned to T1 structures with cranial superimposition too(Fig.5 a-d). The two superimposition processes were performed with point registration and STL registration independently. The endocranial surfaces of the cribriform plate region of the ethmoid bone and the frontal bone were chosen for location of reference points and STL registration. These regions were chosen because of their early completion of growth[28].

After the sequential registration, the T1, T2, T3 models and three reference mandibles (T1r2, T1r3, T2r3) were aligned in the same coordinate system (Fig.5 e-f). The mandibular gross changes which contain mandibular rotation, dentitional changes and condylar growth, mandibular displacement can be assessed by comparing the T1/T2/T3 mandibles. And to distinguish mandibular positional changes without interference of morphological changes, the comparison between virtual reference mandibles (T1r2, T1r3, T2r3) and their corresponding models were applied. There were six mandibles for assessment: T1 mandible, T2 mandible, T3 mandible, T1r2 mandible, T1r3 mandible and T2r3 mandible. And six pairing combinations of these mandibles were compared for evaluation of the morphological and
position changes respectively. The six pairwise combinations of these mandibles were showed as table 1.

### Table 1 the Pairing combination for comparison for mandibular assessment

| Pairing combination for comparison | Purpose                                      |
|-----------------------------------|----------------------------------------------|
| T1 mandible VS T1r2 mandible      | Positional changes between T1 and T2 mandibles |
| T1 mandible VS T1r3 mandible      | Positional changes between T1 and T3 mandibles |
| T2 mandible VS T2r3 mandible      | Positional changes between T2 and T3 mandibles |
| T2 mandible VS T1r2 mandible      | Morphological changes between T1 and T2 mandibles |
| T3 mandible VS T1r3 mandible      | Morphological changes between T1 and T3 mandibles |
| T3 mandible VS T2r3 mandible      | Morphological changes between T2 and T3 mandibles |

### 3. 3D measurement

After registration, the T1, T2, T3 mandibles were aligned in the same coordinate system, the morphological and positional changes were measured independently with aid of the reference mandibles. Treatment, posttreatment, and overall changes were determined by the differences T2-T1, T3-T2, and T3-T1.

**Morphological changes (T1r2 vs T2, T2r3 vs T3, T1r3 vs T3)**

To evaluate the mandibular morphological changes, the comparisons between pairwise mandibles (T1r2 vs T2, T2r3 vs T3, T1r3 vs T3) were performed. The condyle, and alveolar process were our interested regions for assessment of mandibular growth. The condylar volume increment can be measured after 3D subtract booleen operation on pairwise condyles (Fig.6 d). The 3D growth drifts at condyle, mandibular ramus and 3D displacement of mandibular first molars (L6) were evaluated by measuring the Euclidean distances of paired landmarks. The 3D coordinate differences (Δx, Δy, Δz) of the paired landmarks can be calculated respectively for describing the 3D Euclidean distances in each direction (x-, y-, and z-axes) (Fig.6 b,c).

**Positional changes: translation and rotation (T1r2 vs T1 and T1r3 vs T1, T2r3 vs T2)**

After the cranial base superimposition, the reference (T1r2, T1r3, T2r3) and original mandibles (T1, T2) were aligned into the uniform coordinate system, and the reference mandibles can be compared with the original mandibles to evaluate the mandibular positional alterations without the interference of morphological alterations. The translation and rotation of the inertia coordinate systems of two geometry identical objects can be measured using the Calculate 3D Object Position Difference tool (Fig.6 a). An inertia coordinate system is fitted to the selected 3D object with the origin at the center of mass. The rotation angle can measured between the two respective axes of the coordinate systems. And the angles
of three axes (X,Y,Z) were recorded as α, β, γ respectively. And the total translation can be described as three linear distances along the axes (Δx, Δy, Δz). The Euclidean distances of paired landmarks at condylium, mandibular first molars and pogonion on the surface of pairwise mandibles were measured to describe the mandibular 3D displacements. The 3D coordinate differences (Δx, Δy, Δz) of the paired landmarks were calculated in 3 directions: antero-posterior (y axis), vertical (z axis) and transverse (x axis). The 2D details of condylium remodeling and displacements were showed in Figure.7.

**Statistical Analysis**

All measurements were undertaken by a single operator and repeated after 2 weeks at the same console by same operator. The mean values of the 2 measurements were used for final analysis, as recommended by Baumrind and Frantz. Casual and systematic errors were calculated by comparing the values of the first and second measurements, with paired t tests and Dahlberg formula [49]. Descriptive statistics, including the means, standard deviations, minimums and maximums for all variables were calculated. Paired data t-test was used to evaluate differences at different periods (T1-T2, T2-T3, and T1-T3). And the differences 3D condylar growth and displacements (Δx,Δy,Δz ) were evaluated with paired t test. The level of significance was P<0.05. All statistical computations were carried out with a statistical software package for Windows, SPSS ver. 23.0 (IBM Corp., Armonk, NY, USA).

**Results**

Each patient was evaluated with a focus on mandibular changes from the prospective of both the cranial base and mandibular regional superimposition. The establishment of reference mandibles clearly distinguished the morphological changes from positional displacements (table 1). No significant differences (P>0.05) were found in morphological and positional changes at condylar and L6 between right and left sides (table 2).

Table 2 No statistically significant differences between the right and left sides at condyle and L6 was observed with the paired samples t-test.
| Variables | Left | Right | P Value |
|-----------|------|-------|---------|
| Condylar Volume increment | | | |
| T1-T2 | 279.32±18.30 mm$^3$ | 263.39±14.18 mm$^3$ | NS |
| T1-T3 | 253.17±19.12 mm$^3$ | 249.17±17.02 mm$^3$ | NS |
| Morphological 3D Euclidean distances | | | |
| Co(T1-T2) | 1.46±0.25 mm | 1.51±0.31 mm | NS |
| Co(T1-T3) | 1.32±0.19 mm | 1.42±0.17 mm | NS |
| L6(T1-T2) | 4.46±1.01 mm | 4.66±1.33 mm | NS |
| L6(T1-T2) | 4.35±1.14 mm | 4.22±1.54 mm | NS |
| Positional 3D Euclidean distances | | | |
| Co(T1-T2) | 1.11±0.14 mm | 1.07±0.11 mm | NS |
| Co(T1-T3) | 1.92±0.30 mm | 1.88±0.26 mm | NS |
| L6(T1-T2) | 1.72±0.36 mm | 1.81±0.30 mm | NS |
| L6(T1-T3) | 1.77±0.31 mm | 1.83±0.24 mm | NS |

**Treatment changes (T1-T2)**

With the Class II elastic, mesialization and extrusion of the mandibular molars were observed. The mandibular molar moved mesially 4.1 mm and extruded 1.56 mm. The total molar change was 4.55 mm. The mandibular rotation of mandible occurred. In this study, the angles of three axes recorded as $\alpha$, $\beta$, $\gamma$ were used for representation of mandibular 3D rotation. And the angle $\gamma$ was negligible and we presumed the x axis is stable without rotation. The 3D rotation was simplified to 2D rotation around X axis and measured in YZ plane as 2D angle. The rotation change during orthodontic treatment (T1-T2) was 1.03 degree and the mandibles rotated backwardly and downwardly. After treatment, the mandibular position changed with total translation 1.64 mm and the direction of the translation was downward and backward. The true displacements at the landmarks of Co, L6 and Pog were calculated with comparison of T1 and T1r2 mandibles and recorded in Table 3. The compensatory condylar remodeling after treatment was observed. The growth volume at condyle was $271.35±16.24$ mm$^3$ and vertical increment of condyle was 1.43 mm. The condylar growth and displacement did not match in three directions. The vertical condylar growth and displacement ($\Delta z$) were significantly different ($p < 0.05$; Table 4). The sagittal growth and displacement ($\Delta Y$) were significantly different ($p < 0.05$; Table 4). The downward displacement at condylion was less than the vertical growth, and the vertical increment of condyle did not induce the isometric displacement and the forward rotation was restricted, the comparison between 3D growth and corresponding 3D displacement at condylion was recorded in Table 5.
Table 3 Comparison of T2 (T1r2 vs T2) and T3(T1r3 vs T3) morphological changes with the paired samples t-test.

| Variables                        | T2       | T3       | P Value |
|----------------------------------|----------|----------|---------|
| Condylar volume changes (mm³)    |          |          |         |
| Co                               | 269.12±14.56 | 251.19±14.11 | NS      |
| 3D growth drift at Co (mm)       |          |          |         |
| Euclidean distances              | 1.43±0.24 | 1.69±0.32 | *       |
| Δx                               | 0.12±0.15 | 0.16±0.10 | NS      |
| Δy                               | 0.24±0.19 | 0.68±0.15 | *       |
| Δz                               | 1.35±0.30 | 1.24±0.23 | NS      |
| 3D growth drift at L6 (mm)       |          |          |         |
| Euclidean distances              | 4.55±1.01 | 4.06±1.13 | *       |
| Δx                               | 0.73±0.28 | 0.65±0.19 | NS      |
| Δy                               | 4.10±1.06 | 4.22±0.96 | NS      |
| Δz                               | 1.56±0.43 | 1.37±0.47 | *       |

Values are presented as mean ± standard deviation.

*=P <0.05   NS: No significant differences

Table 4 Comparison of T2 (T1r2 vs T1) and T3(T1r3 vs T1) positional changes with the paired samples t-test.
| Variables                  | T2               | T3               | P Value |
|----------------------------|------------------|------------------|---------|
| 3D rotation (°)            |                  |                  |         |
| φ                          | 1.03±0.15°       | 0.36±0.05°       | *       |
| β                          | 1.04±0.12°       | 0.39±0.10°       | *       |
| θ                          | 0.15±0.11°       | 0.20±0.04°       | NS      |
| Total translation (mm)     |                  |                  |         |
| Total translation          | 1.64±0.23        | 1.79±0.31        | NS      |
| 3D displacement at Co (mm) |                  |                  |         |
| Euclidean distances        | 1.12±0.19        | 1.97±0.35        | *       |
| Δx                         | 0.27±0.15        | 0.41±0.21        | NS      |
| Δy                         | 1.01±0.31        | 0.85±0.22        | *       |
| Δz                         | 0.08±0.10        | 1.67±0.32        | *       |
| 3D displacement at L6 (mm) |                  |                  |         |
| Euclidean distances        | 1.70±0.39        | 1.76±0.36        | NS      |
| Δx                         | 0.28±0.10        | 0.30±0.22        | NS      |
| Δy                         | 1.61±0.33        | 1.71±0.24        | NS      |
| Δz                         | 1.65±0.22        | 1.55±0.45        | NS      |
| 3D displacement at Pog (mm)|                  |                  |         |
| Euclidean distances        | 2.23±0.42        | 1.62±0.39        | *       |
| Δx                         | 0.30±0.15        | 0.13±0.11        | NS      |
| Δy                         | 1.78±0.34        | 1.08±0.13        | *       |
| Δz                         | 1.55±0.29        | 1.21±0.28        | *       |

Values are presented as mean ± standard deviation.
* = P <0.05  NS: No significant differences

Table 5 Comparison between 3D growth and corresponding 3D displacement at condylion.
| Variables                   | Condylar growth (mm) | Condylar displacement (mm) | P Value |
|-----------------------------|----------------------|----------------------------|---------|
| T1-T2 (mm)                  |                      |                            |         |
| Euclidean distances         | 1.43±0.24            | 1.12±0.19                  | *       |
| Δx                          | 0.12±0.15            | 0.27±0.15                  | NS      |
| Δy                          | 0.24±0.19            | 1.01±0.31                  | *       |
| Δz                          | 1.35±0.30            | 0.08±0.10                  | *       |
| T1-T3 (mm)                  |                      |                            |         |
| Euclidean distances         | 1.39±0.32            | 1.97±0.35                  | *       |
| Δx                          | 0.16±0.10            | 0.41±0.21                  | NS      |
| Δy                          | 0.22±0.15            | 0.85±0.22                  | *       |
| Δz                          | 1.24±0.23            | 1.67±0.32                  | *       |

Values are presented as mean ± standard deviation.

*=P <0.05    NS: No significant differences

**Overall changes (T1-T3)**

The overall changes between T1 and T3 were measured and recorded. The paired t test statistical comparison of the treatment (T1-T2) and overall variables (T1-T3) was presented in Table 3 and 4. There was statistically significant differences between the treatment and overall variables regarding the 3D rotation, condylar displacement, Pog displacement (Table 4). Comparing with the treatment changes, the mandibular rotation was reduced and the condyle moved back to its initial position in the overall changes. The continuous condylar remodeling and mandibular rotation/translation in the retention stage must occurred.

**Posttreatment changes (T2-T3)**

After the retention stage, the continuous morphological and positional changes occurred (table 6). The sagittal growth at condyle was found and induced forward displacement of condyle. The total translation of T3 mandible from T2 mandible was 1.46 mm in average and the direction of the translation was downward and forward. The downward/forward displacements of condyle (Δz) was 1.64/0.68 mm and induced 1.60 mm forward displacement (Δy) at pogonion and 0.95 degree forward rotation of mandible. The backward rotation during treatment period (T1-T2) was neutralized by the T2-T3 forward rotation.

Table.6 the morphological and positional changes of posttreatment stage (T2-T3).
### T2-T3 changes

| Morphological changes | Euclidean distances | \( \Delta x \) | \( \Delta y \) | \( \Delta z \) |
|-----------------------|--------------------|----------------|----------------|----------------|
| Condyle               |                    | 0.59±0.10 mm   | 0.57±0.08 mm   | 0.11±0.08 mm   |
| L6                    |                    | 0.54±0.08 mm   | 0.41±0.17 mm   | 0.46±0.11 mm   |

| Positional changes | 3D rotation | \( \beta \) | \( \gamma \) |
|--------------------|-------------|-------------|-------------|
| 0.95±0.20°         | 0.97±0.25°  | 0.20±0.05°  |

| Co                  | Euclidean distances | \( \Delta x \) | \( \Delta y \) | \( \Delta z \) |
|--------------------|--------------------|----------------|----------------|----------------|
|                    | 1.78±0.33 mm       | 0.32±0.22 mm   | 0.68±0.11 mm   | 1.61±0.32 mm   |

| L6                  | Euclidean distances | \( \Delta x \) | \( \Delta y \) | \( \Delta z \) |
|--------------------|--------------------|----------------|----------------|----------------|
|                    | 1.07±0.32 mm       | 0.10±0.11 mm   | 1.01±0.21 mm   | 0.68±0.20 mm   |

| Pog                 | Euclidean distances | \( \Delta x \) | \( \Delta y \) | \( \Delta z \) |
|--------------------|--------------------|----------------|----------------|----------------|
|                    | 1.65±0.44 mm       | 0.06±0.13 mm   | 1.60±0.37 mm   | 0.62±0.31 mm   |

## Discussion

To evaluate within-subject changes, image superimposition of different phases is the most effective and popular method [17,25]. Comparison after longitudinal 3D superimposition has the potential to assess bone displacements and remodeling. A significant amount of knowledge about facial growth and orthodontic treatment results comes from tracings of 3D image superimpositions [22,23,26,27,30]. And in 3D CBCT superimposition, the cranial base is most widely used as a stable reference structure [31-33]. With the 3D superimposition basing on cranial base, overall facial changes relative to the cranial base can be unraveled, and the mandibular changes that are sum of positional and morphological changes cannot be completely defined respectively. To fully understand mandibular growth and response to treatment, mandibular regional superimpositions are required to separate morphological changes from positional changes. Recently 3D voxel based mandibular regional superimpositions have been validated to be accurate and reproducible [26,27]. Tung Nguyen et al demonstrated that both the chin and symphysis regions generated precise superimpositions and the anterior contour of the chin and the internal symphysis were stable with growth [26]. 3D images registration based on these stable areas of mandible
can visualize and quantify mandibular growth and modeling. Cranial base superimpositions in combination with mandibular regional superimpositions can define exact mandibular growth and rotation.

The morphological changes can be quantitatively assessed after mandibular regional superimposition by comparing two mandibular models directly [22,34,35]. However, the 3D mandibular positional changes can not be evaluated exactly with morphological interference. The mandibular rotational changes must be calculated between two geometry identical objects. So to distinguish the morphological from positional changes and eliminate mutual interference, the reference mandible (Tr) with both T1 morphology and T2 position is necessary for thorough mandibular evaluation. The sequential 3D superimpositions combated cranial base superimpositions with mandibular regional superimpositions can generate the reference mandible and quantify the morphological and positional changes.

The present study investigated the effects of orthodontic elastic treatment of Class II, division 1 malocclusions on mandibular rotation and mandibular displacement with the 3D superimposition. Similar to previous numerous studies [36,37], we demonstrated that orthodontic class II elastic induced mandibular displacement as well as mandibular rotation. This finding confirmed the observations of previous studies. Odegaard [38,39] carried out implant studies showed that mandibular rotation was related to the amount and direction of condylar growth. Isaacson et al [40,41] reported that mandibular displacement is translatory when the increments of vertical condylar growth equal the increments of vertical growth at the maxillary sutures and the maxillary and mandibular alveolar processes. However, if condylar growth exceeds the vertical growth at the sutural-alveolar process area, a forward or closing mandibular rotation would occur and vice versa. In this study, the condylar growth, backward and forward rotations were observed. During the treatment period, the results indicated the class II elastics extruded the molars and rotated the mandible backwardly. Though the compensatory condylar adaptive remodeling occurred, the corresponding downward displacement of condyle did not observed and the mandibular rotation around a center located in the area of the TMJ that was referred to as Type I backward rotation. The functional relationship between condyle and glenoid fossa was changed. And in retention stage, the results indicated the continuous positional changes did not cease and the mandible still adapted in order to maintain its functional relationships. The downward displacement at Co and upward displacement at Pg were observed and the Type II backward rotation occurred and neutralized the backward rotation in treatment stage. So in the overall stage, the main positional changes (T1-T3) were downward translations with slight rotation. The sequential 3D superimpositions revealed the complex process of mandibular rotation and indirect orthopedic effects of orthodontic Class II elastic to condylar regional adaptive growth. The findings in this study presented a better understanding of how the mandible adapt to maintain its functional relationships.

In this study, the condylar adaptive growth response to orthodontic class II elastic which was seldom mentioned in previous studies was demonstrated. The most marked uniqueness of condylar cartilage lies in its capability of adaptive remodeling in response to external stimuli during or after natural growth [42]. The clinical application of functional appliances is based on the notion that the condyles adapt to the
altered mandibular position. While it is generally accepted that functional appliances alter mandibular growth, the orthodontic force also can induce condylar adaptive remodeling indirectly due to the mandibular backward rotation and occlusal vertical increment. The condylar adaptive remodeling can be stimulated not only mandibular advancement with functional appliances but also slight mandibular positional changes with orthodontic elastics. The capability of adaptive remodeling of condyles can regulate the equilibrium of maxillofacial system and maintain adequate joint function. The slow and continuous condylar remodeling may be one of the factors to orthodontic relapse. In this study, the labial relapse of maxillary incisors can be observed and accompanied with the mandibular forward rotation [43]. The condylar adaptive remodeling process did not cease until a new maxillofacial equilibrium was established.

To eliminate the interference of natural growth and unreveal the pure condylar adaptive response, all subjects in this study were adult after natural growth. The previous experiments in adult rats have revealed that the repositioning of the mandibular condyle led to a reactivation of chondrogenesis in condylar cartilage which otherwise is at resting status, and finally results in increased bone formation [44]. Beside the animal experiments, the adaptive condylar remodeling in adult patients has been clarified in the studies of 3D evaluation after orthognathic surgery because orthognathic surgery inevitably results in condylar positional changes [45]. So the adaptive capacities of the condyle may present throughout post-natal life and retain the potentiality of TMJ to regulate the equilibrium of maxillofacial system. In this study, we demonstrated that the condyle in adult did undergo adaptive response but the adaptive remodeling did not complete even in the retention period. So the process of condylar adaptive remodeling in adult was slow and limited, the orthodontists must avoid excessive vertical occlucal alteration and do not exceed the adaptive capacity of the joint.

In the 2D decade, orthodontists have long been aware that mandibular rotation takes place during growth, orthodontists have underestimated its importance of mandibular growth rotation and understand that true rotation is the primary determinant of chin position and a major determinant of condylar growth direction, mandibular modeling, and dentoalveolar compensations [46]. True mandibular rotation provides important information for understanding facial growth changes, especially changes of the chin. Mandibular rotation has been extensively studied since Björk7 introduced a new method of studying mandibular growth and modeling in living subjects [47]. To fully describe the positional changes of the mandible in 3D space, the translation along three direction and rotation about 3 perpendicular axes is essential in 3D decade [48]. In this study, the reference mandible method make it possible for understanding of the 3D multiple mandibular rotation (ie. facial asymmetry), and leads to a better understanding of the facial growth process and opens up new treatment possibilities.

Declarations

Ethical approval and consent to participate
Ethical approval for the study was obtained from the Biomedical Ethics Committee of Shandong Hospital of Stomatology and all subjects signed informed consents prior to the study (201165). All methods were performed in accordance with the relevant guidelines and regulations with the Ethical approval.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Competing interests

The authors had no competing or conflict of interest whatsoever.

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Author contributions statement

D.X.L. designed the research, reviewed and revised the manuscript and approved the final manuscript as submitted, and obtained funding for the project. L.H. collected the data, carried out the research, measured and analyzed the data. X.X. analyzed and discussed the results, and drafted collected the data, and carried out the research. All authors reviewed the manuscript.

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Various threshold values were selected for 3D reconstruction of maxillia, mandible, the cranical base and the mandibular chin. All the models of T1,T2,T3 were econstructed respectively.
the T1 mandible and chin were imported into T2 project (a), the T1 mandible and chin were registered to T2 mandible with point registration (b) and STL registration (c) with the chin and symphysis as stable reference regions. The T1 mandible was placed at the T2 positions and defined as reference mandible T1r2 (d).
the T1r2 mandible, T2 mandible and chin were imported into T3 project (a), the mandibular regional superimposition between T1r2, T2 mandible and T3 mandible were performed with point registration and STL registration independently with chin as stable reference (b and c). The T1r2 and T2 mandibles were aligned to T3 mandibular position and defined as T1r3 and T2r3 mandibles for positional assessment (d).
Figure 4

the T2 cranial base, maxillary, mandible and T1r2 mandible were imported into T1 project (a), the global superimposition were performed with point registration (b) and STL registration (c) independently by using the anterior cranial fossa as the reference. The superimposition between T1 and T2 mandibles were completed and there were three mandibles (T1, T2 and T1r2) for the following measurement (d).
Figure 5

the T3 models, T1r3, T2r3 mandibles were imported into T1 project (a), and after point registration (b) and STL registration (c) of cranial base, the registration between T3 and T1 mandibles were completed (d), and the T1, T2 and T3 projects were aligned in the same coordinate system (e), the T1,T2,T3, T1r2,T1r3 and T2r3 mandibles were aligned together for calculating positional and morphological changes(f).
Figure 6

the T1 and T1r2, T1r3 mandibles are geometry identical objects, the translation and rotation can be calculated with Calculate 3D Object Position Difference tool in the Mimics software by comparing the T1 and T1r2, T1 and T1r3, T2 and T2r3 mandibles (a). The pure translation at condylion, mandibular first molars and pogonion were measured (T1r2 vs T1 and T1r3 vs T1, T2r3 vs T2) and the morphological changes at condylion, mandibular first molars were calculated (T1r2 vs T2, T2r3 vs T3, T1r3 vs T3), the 3D coordinate differences ($\Delta X$, $\Delta Y$, $\Delta Z$) of the landmarks can be calculated for the following analysis (b,c). The growth volume at condyles can be separated and quantified after the 3D boolean operation of T1r2 and T2 mandibular models (d).
Figure 7

A 2D perspective of condyle for description of the morphological and positional changes with the contour line of the registered mandibular models. The T1-T2 treatment changes (a,e,i), the T1-T3 overall changes (b,f,j), the T1-T2 posttreatment changes (c,g,k) and the merged T1-T2-T3 changes (d,h,i) were listed as 4×3 form. The total changes (a-d), the positional changes (e-h), the morphological changes (i-k) can be measured and compared respectively. All the changes were merged together in fig.l.