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Research Paper
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New approach to establish an object reference frame for dental arch in computer-aided surgical simulation

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Abstract. The purpose of this study was to develop a principal component analysis-based adaptive minimum Euclidean distances (PAMED) approach to establish an optimal object reference frame for symmetrical alignment of the dental arch during computer-aided surgical simulation (CASS). It was compared with our triangular methods and the standard principal component analysis (PCA) method. Thirty sets of maxillary digital models were used. Midsagittal and occlusal planes were ranked by three experienced evaluators based on their clinical judgment. The results showed that for the midsagittal plane, all three evaluators ranked ''ideal'' for all 30 models with the PAMED method, 28 with the triangular method, and at least 11 with the PCA method. For the occlusal plane, one evaluator ranked all 30 models ''ideal'' with both the PAMED and the PCA methods while the other two evaluators ranked all 30 models ''ideal'' with the triangular method. However, the differences among the three methods were minimal. In conclusion, our PAMED method is the most reliable and consistent approach for establishing the object reference frame for the dental arch in orthognathic surgical planning. The triangular method should be used with caution because it can be affected by dental arch asymmetry. The standard PCA method is not recommended.

Key words: object reference frame; dental arch; symmetrical alignment; midsagittal plane; occlusal plane; orthognathic surgery; computer-aided surgical simulation; surgical planning.

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An important step in orthognathic surgical planning is to restore the symmetrical alignment of a dental arch with reference to the whole face[1–4]. Analyzing dental arch symmetrical alignment requires an object reference frame, previously called a local coordinate system[1] or a local reference frame[4]. Like the global reference frame for the whole face, the object reference frame for a dental arch is composed of three orthogonal planes. The axial plane divides the dental arch into upper and lower halves; the coronal plane divides the arch into front and back halves; and the midsagittal plane evenly divides the arch into right and left halves evenly. By comparing the object reference frame for the dental arch to the global reference frame for the whole face, the symmetrical

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alignment of the dental arch can be calculated as a transverse difference in the central incisal midpoint (dental midline), and orientational differences in yaw and roll (cant)[1–4].

Currently, there are no reports on how to establish an object reference frame for a dental arch for digitally planning orthognathic surgery. A common practice is to place a transparent ruled grid over the dental cast and align it to the midpalatal raphe, so that a clinician can visually spot asymmetry of the arch form[5,6]. The median palatal suture is used as the center of the maxillary dental arch and the symmetry axis. However, the dental midline rarely coincides with the median palatal suture even after orthodontic treatment. Ferrario et al.[7] used the line connecting the centers of gravity of the anterior and poster teeth to determine the axis of symmetry. However, this method can only be used in patients with perfectly symmetrical dental arches[8]. Nonetheless, all of these methods only define the median line for the arch and none can be used to construct an object reference frame for the dental arch. Without using an object reference frame, the midline deviation may only be corrected by using the median line of the dental arch; the correction of the yaw and roll misalignments of the dental arch remains problematic.

In the past, our Surgical Planning Laboratory developed a triangular method in computer-aided surgical simulation (CASS) to analyze the symmetrical alignment for the dental arches (Fig. 1). This method utilizes three points: the midpoint between the two central incisal embrasures (U0), and the right and left mesiobuccal cusps of the first molars (U6)[1–3]. In this method, the origin of the object reference frame is U0. The axial plane is the occlusal plane constructed using these three landmarks. The midsagittal plane is the plane that passes through U0 and evenly divides the arch into right and left halves. The coronal plane is perpendicular to both the axial and the midsagittal plane. This triangular method is simple and easy to implement. However, it was developed based on the authors' experience during the utilization of CASS planning and has not been formally evaluated. In addition, we found that the triangular method was not reliable when there was dental arch asymmetry of any etiology, for example, unilateral edentulism, or individual tooth misalignment. Any of the above conditions can skew the triangular method and cause errors in defining the object reference frame.

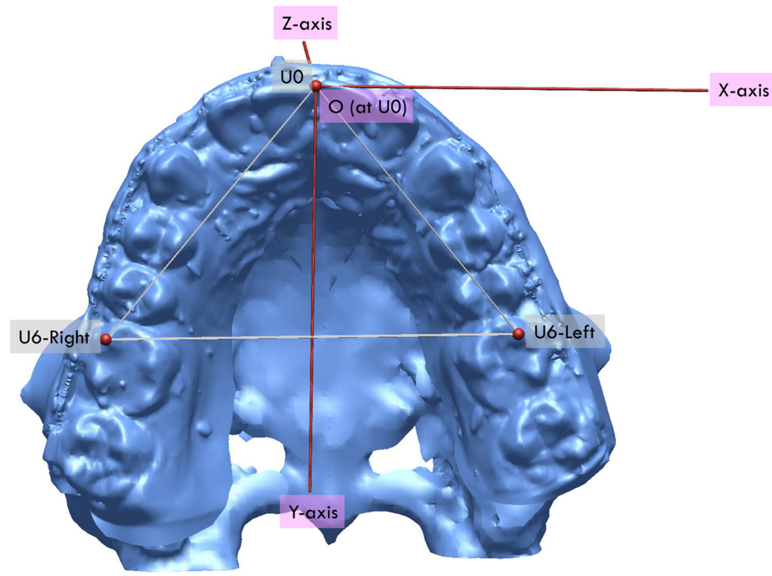

Fig. 1. Triangular method. It utilizes three points: midpoint between the two central incisors (U0), and right and left mesiobuccal cusps of the first molars (U6).

It is the authors' belief during CASS planning that the symmetrical alignment of the dental arch can only be correctly analyzed when the object reference frame, especially the midsagittal plane, is correctly established. Our hypothesis is that the use of more dental landmarks will improve the accuracy of establishing an object reference frame for the dental arch. To this end, we developed a principal component analysis-based adaptive minimum Euclidean distances (PAMED) method to estimate an optimal object reference frame for a dental arch. This PAMED method was then compared with our triangular method[1–4] and the standard principal component analysis (PCA) method[9,10].

Materials and methods

Thirty sets of patients' maxillary digital and stone dental models were used in this study. Using a random number table, the models were randomly selected from our dental model archive for patients with dentofacial deformity. The inclusion criteria were (1) patients who had received preoperative orthodontic treatment and had undergone either one-piece or multipiece Le Fort I osteotomy; (2) the maxillary models had been used to establish a stable final occlusion during the surgical planning. In the case of the multipiece Le Fort I osteotomy, the models had been segmentalized and hand articulated by surgeons at the time of CASS planning. The research protocol was approved by our institutional review board (IRB(2) 1011-0187x).

Three methods were used to establish the object reference frame for each dental arch, including PAMED (Figs 2 and 3), and the triangular (Fig. 1) and the standard PCA (Fig. 4) methods. The computation was programmed using MATLAB 2014a (The MathWorks, Inc, Natick, MA), and the calculation was completed in real time. The landmarks used in these three methods are listed in Table 1.

Evaluation

The object reference frames established using the three methods were evaluated by three evaluators, including two oral and maxillofacial surgeons who were experienced in orthognathic surgery (C.-M.C. and D.C.-Y.H.) and an orthodontist (Y.-F.L.). A random number was assigned to each method within each model so that the evaluators were blinded to the methods used for establishing the object reference frames. They were also blinded to each other's evaluation results.

Since there was no ''gold standard'' for establishing the object reference frame for a dental arch, the evaluators were instructed to evaluate the results using their best clinical judgment as if they were performing dental arch analysis in their routine clinical practice. The midsagittal (YOZ) plane and the occlusal plane (either XOY or X′O′Y′ plane) were evaluated separately. The coronal plane was not evaluated since it was naturally derived