# Automated Three-Piece Digital Dental Articulation

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**Abstract.** In craniomaxillofacial (CMF) surgery, a critical step is to reestablish dental occlusion. Digitally establishing new dental occlusion is extremely difficult. It is especially true when the maxilla is segmentalized into 3 pieces, a common procedure in CMF surgery. In this paper, we present a novel midline-guided occlusal optimization (MGO) approach to automatically and efficiently reestablish dental occlusion for 3-piece maxillary surgery. Our MGO approach consists of 2 main steps. The anterior segment of the maxilla is first aligned to the intact mandible using our ergodic midline-match algorithm. The right and left posterior segments are then aligned to the mandible in sequence using an improved iterative surface-based minimum distance mapping algorithm. Our method has been validated using 15 sets of digital dental models. The results showed our algorithm-generated 3-piece articulation is more efficient and effective than the current standard of care method. The results demonstrated our approach's significant clinical impact and technical contributions.

## 1 Introduction

Craniomaxillofacial (CMF) surgery involves surgical correction of congenital or acquired deformities of the skull and face. Throughout the world, many patients suffering from CMF deformity require surgical correction. In the CMF surgery, one of the critical steps is to reestablish a good dental occlusion (the relationship between the upper and the lower teeth). Current standard of care to reestablish occlusion (called *stone dental cast surgery*) is very convoluted and time-consuming. When a doctor uses upper and lower stone dental casts to establish the occlusion (called *dental articulation*), the physical action of articulating upper and lower models into a maximal contact (called *maximum intercuspation (MI)*) is relatively easy and accurate. It becomes more difficult when the maxilla is segmentalized into 3 individual segments, 1 anterior and 2 posteriors (usually takes 4-6 hours manually). Each individual piece has its own 6-degree of freedom and lesser geometric features that can be extracted for dental articulation. The process of articulating the 3 upper segments to the lower teeth is a common procedure in CMF surgery (called *3-piece articulation*). In this procedure, lower dental arch usually remains intact. The dental articulation becomes even more difficult in virtual world, where the digital dental models are represented by three-dimensional (3D) images that lack collision constraints [1].


N. Navab et al. (Eds.): MICCAI 2015, Part I, LNCS 9349, pp. 488–496, 2015.
DOI: 10.1007/978-3-319-24553-9_60

Generally, the following rules are applied to the dental articulation: the upper and lower teeth should be maintained in MI; and both upper and lower central dental midlines should be aligned straight in the middle. Additional rules are applied to the 3-piece dental articulation: the anterior and the two posterior segments should maintain an appropriate smoothly curved relationship in the new upper dental arch, and to their corresponding lower dental arch; the upper and lower incisors should maintain appropriate overbite and overjet (vertical and horizontal distances between the upper and lower incisors); and the new upper dental arch should maintain appropriate Curve of Wilson (a U-shape curve in front view) between the posterior segments.

Currently, there is no report on establishing the 3-piece dental articulation digitally. Only the research works on 1-piece articulation were reported. Hiew et al. [2] described a technique in which plaster orthodontic study models with their distinctive heptagonal bases were created for a corresponding set of upper and lower dental models. DeLong et al. [3] proposed to align a set of digital dental models into MI based on three-point alignment. Zhang et al. [4] developed a two-stage occlusal analysis algorithm to manually align the models in the computer. However, none of above approach can be actually used in real clinical practice. More recently, Chang et al. [1] developed an approach to achieve single-piece dental articulation using an Iterative Surface-based Minimum Distance Mapping with collision constraints (ISMDM). Although this approach was validated clinically, it could be only used for 1-piece dental articulation, but not for 3-piece articulation.

In this article, we present a novel and effective midline-guided occlusal optimization (MGO) approach to automatically reestablish dental occlusion for 3-piece maxillary osteotomy (within 30 minutes using MATLAB codes on a regular office PC). Our MGO approach includes two main steps. The first step is to align the maxillary anterior segment to the intact mandible based on a robust ergodic midline-match algorithm. The second step is to align the right and left posterior segments to the mandible in sequence using an improved ISMDM optimization algorithm combined with occlusal plane transformation, new constraints for deviations among the 3 pieces, and adaptive constraints parameter adjustment. Finally, our method is validated using 15 sets of dental models that are required for 3-piece dental articulation. The clinical contribution of this project is significant. It allows clinicians to plan CMF surgery completely in the computer, including the most challenging 3-piece digital dental articulation. This has never been achieved before. The plan can then be transferred to the patient at the time of the surgery using surgical templates [5]. The technical contribution is that our novel ergodic midline-match algorithm can ensure the upper and lower dental midlines are ideally aligned to each other, and the arc of the anterior segment is aligned to the lower dental arch with their incisors maintaining appropriate overjet, overbite and inclination. Additionally, guided by the midline-matched anterior segments, our MGO approach further applies an improved ISMDM aligning the two posterior segments of the upper model to the lower model to ensure they are in MI.

## 2 Algorithm for Automatic 3-Piece Dental Articulation

The 3 pieces of the upper digital dental model and the intact lower dental model are represented by closed mesh surfaces. For 3-piece dental articulation, we need to align not only the occlusal surfaces between the upper and lower teeth, but also the cutting surfaces among the anterior and the two posterior segments of the upper model. In our algorithm, we first extract dental features for both the occlusal and cutting surfaces.

The occlusal surfaces feature points are extracted based on the work in [1]. For cutting surface feature points, a kd-tree [6] is constructed for mesh vertices on the anterior segment of maxilla. The nearest neighbor search (NN) algorithm is then applied to find the closest points between the posterior and anterior segments of maxilla. Finally, the cutting surface feature points are constructed from the closest points. Fig. 1 shows the feature points of the occlusal and cutting surfaces for the 3-piece upper models, and the occlusal feature points for the lower model. These feature points are used for the alignment of the anterior and two posterior segments. They are described below in details.

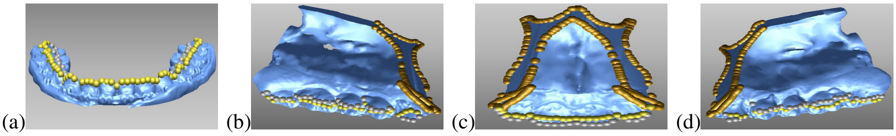



**Fig. 1.** Feature points for occlusal and cutting surfaces. (a) lower model; (b) right posterior segment of upper model; (c) anterior segment of upper model; (d) left posterior segment of upper model. Light yellow and Gray represent occlusal surface feature points. Dark yellow represents cutting surface feature points.

### 2.1 Anterior Segment Alignment

Anterior alignment plays an important role in dental occlusion. In our 3-piece MGO approach, we first align the anterior segment to an ideal position based on a group of clinical rules, followed by right and left posterior segment alignment. We develop an ergodic midline-match algorithm to solve the anterior segment alignment problem.

The midline-match algorithm is to align the dental midlines of the upper anterior segment and the lower teeth, and to set an appropriate overjet and overbite. For a given target overjet and overbite with a resulted upper and lower incisal inclination (calculated based on overjet and overbite), we can estimate a new position of upper midline plane (black intersectional lines in Fig. 2(a)) based on lower midline plane (green intersectional lines in Fig. 2(a)). Each central incisal midline plane is determined by manually digitizing 2 midpoints of right and left incisal edges, and a midpoint between the 2 roots (the circles in Fig.2). A transform matrix is then calculated by matching the original (red in Fig. 2(a)) and estimated upper midline planes. During the alignment, the upper and lower dental midlines are perfectly aligned to each other with appropriate overjet and overbite. The arc of the anterior segment is also aligned to the arc of the lower dental arch (blue in Fig. 2(a)).

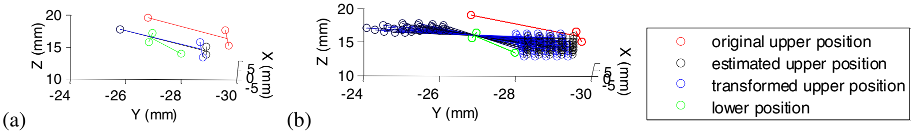



**Fig. 2.** Schema of ergodic midline-match transform; (a) a given transform; (b) ergodic transforms.

In order to eliminate any possible penetration between the anterior segment of upper teeth and lower teeth, a penetration-adjustment procedure is applied to the initial midline-matched upper and lower models. The penetrations are detected by finding the intersection of the lower teeth surface and the transformed upper anterior segment surface. The penetrations are eliminated by performing a pitch rotation (rotating around the mediolateral axis) of the upper anterior segment. The pitch rotational angle is computed based on the penetrated points between lower and upper surfaces.

It is challenge to determine a definitive combination of overjet, overbite and the inclination of the upper and lower incisors, since the clinical normative value of each measurement has a mean and a standard deviation. Therefore, in our algorithm, we generate a series of anterior segment midline-match transformations in a range of overjet, overbite and inclination between the upper and lower incisors using clinical norms (Fig. 2 (b)). Overjet is set in a range of 1.4 - 2.6mm (0.3mm per step) while overbite is set in a range of 0.5-2.5mm (0.4mm per step) [7]. The algorithm generates a total of 30 positions for midline-matched upper models. All the midline-matched upper models are then ranked based on clinical criteria (the balance among overjet, overbite and the resulted inclination of the upper and lower incisors (normal value: 131±11° for male and 136±11° for female [7])). At this stage, both the right and left posterior segments are transformed together with the anterior segment without breaking their original relationship. Finally, top 5 optimal positions of the anterior segment are automatically determined based on normal values and saved for the next step.

## 2.2 Right and Left Posterior Segments Alignment

After the anterior segment of the upper dental model is aligned to the lower dental model, the right and left posterior segments are individually articulated to the mandible. We develop an improved ISMDM algorithm to achieve the posterior segment alignment. The original ISMDM algorithm [1] iteratively minimizes the distance of 1-piece upper and lower occlusal surfaces to acquire an MI using small-angle approximation and quadratic optimization. It requires an initial alignment of the upper model to the lower model by matching the whole occlusal surfaces feature points. However, in 3-piece dental alignment, the use of the full occlusal surfaces feature points matching cannot achieve a rough alignment of the 3 pieces of upper model to the lower model. Three-piece articulation requires more constraints for the relationships between the anterior and posterior segments. To solve these problems and ensure that the optimization is feasible and convergent, we improve the ISMDM by developing an occlusal plane transform method to align the upper posterior segments to the lower model with extra constraints in the framework of ISMDM. The constraint parameters are adjusted adaptively during the iterative optimization process.

In the occlusal plane transformation, three distinct feature points (canine cusp *P1*, the 1st molar mesiobuccal cusp *P2*, and 1st molar mesiopalatal cusp *P3*) on the posterior segment are used to guide the transformation. Clinically, we have a definition on where each cusp of the upper teeth should be around the corresponding lower teeth. Using these clinical rules, we can automatically estimate initial positions of these feature points (*P1'*, *P2'*, *P3'*). A rigid transformation is thus calculated and applied to the posterior segment to roughly align it to the lower model.

Based on the initial alignment, the optimal alignment is achieved by minimizing the distance of the two pairs of feature points (shown in Fig. 1) on posterior occlusal surfaces:

$$d_S^2(R,t) = \frac{1}{N}\sum_{j=0}^{N-1} \left\| u_{i_j} - v_j'(R,t) \right\|^2 \tag{1}$$

where, $v_j'$ is the transformed feature point of $v_j$ on the posterior segment, $u_{i_j}$ is the matched feature point of $v_j$ on the mandible, $N$ is the number of feature points on the posterior segment, $R$ is the rotation matrix and $t$ is the translation vector. In addition, the posterior segment should maintain an appropriate smoothly curved relationship with the anterior segment. Therefore, we add a deviation constraint to limit the distance (within a range of 0-2mm) of a cutting surface feature point $a_j$ on the posterior segment, and the corresponding cutting surface feature point $b_j$ on the anterior segment. The constraint is $\left\|a_j - b_j\right\|^2 < h_1$, where $h_1$ is the threshold distance (2mm) [8]. We also use a deviation constraint between upper canine $p_1$ and lower interstices between canine and 1st premolar $p_2$, $\|p_1 - p_2\|^2 < h_2$ ($h_2$ is a threshold distance, also 2mm). This constraint is to achieve a correct canine intercuspation.

By only using small-angle approximation with the two extra constraints, the iterative quadratic optimization may be infeasible. Therefore, we adjusted the constraint parameters $h_1$ and $h_2$ adaptively during the iterative optimization process. Large parameter values are used first to start the iterative optimization process. Once the iteration became feasible, the parameters are then gradually adjusted to a strict level until the optimization converged.

## 3 Experiments and Results

### 3.1 Dental Models and Digital Dental Articulation

**Patient Digital Dental Models.** A total of 15 sets of patient digital dental models were randomly selected from our digital archives [IRB(2)#1011-0187x]. Each patient dataset included a set of hand-articulated 3-piece upper and 1-piece corresponding lower dental models, and an unarticulated original uncut upper model. The digital dental models (in .STL format) were generated using a high-resolute laser scanner. The hand articulated 3-piece upper and lower dental models were achieved using a current standard of care method [9], scanned together, and used in the actual surgery.

They served as reference models (controls). In the computer, the stand-alone uncut upper dental casts were manually segmentalized into 3 pieces between lateral incisors and canines without disturbing the relationship among the 3 pieces. The stand-alone 3-piece upper digital models served as an experimental group.

**Three-Piece Digital Dental Articulation.** In order to compare our algorithm-articulated 3-piece models to the reference models, we used the reference lower dental model as the target. The 3-piece segments of each experimental model were automatically articulated to the reference lower model using our MGO approach within 30 minutes. All codes were written in MATLAB and run on a regular office PC. A total of 5 articulated 3-piece upper models for each patient were generated. They were evaluated together with the reference models qualitatively and quantitatively.

### 3.2 Qualitative Validation and Results

In order to qualitatively validate our method, 3 experienced evaluators (2 oral surgeons and 1 orthodontist) were asked independently to evaluate our results. The evaluation was conducted in two steps. The first step was to rank the blinded 6 sets of 3-piece articulated models (1 reference and 5 algorithm-generated models) for each patient, while the second step was to evaluate whether the best ranked algorithm-articulated model in each patient was ready for the surgery by comparing it to the unblind reference model.

In the first step of the evaluation, the 6 sets of models for each patient were shown as a group to the evaluators. The order of them was randomly generated and the evaluators were blind to the nature of the models. The evaluators were asked to give a rank to each of the 6 models based on the clinical criteria, i.e., upper and lower midlines, arcs of the upper and lower dental arch alignment, appropriate overjet, overbite and inclination, MI, and appropriate Curve of Wilson. A rank of "6" indicated the best articulated models while a score of "1" indicated the worst.

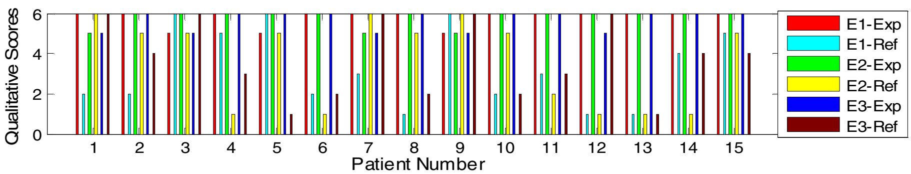



**Fig. 3.** Comparisons between the best rank of the algorithm-articulated model and the rank of reference model when were blended together. E1-, E2- and E3-Exp: 3 evaluators' the best ranked algorithm-articulated models; E1-, E2- and E3-Ref: 3 evaluators' ranks for reference models.

The results of the blind evaluation were shown in Fig. 3. For each patient, only the best rank of the algorithm-articulated models and the rank of the reference model were shown (due to the page limit). While all 3 evaluators agreed that 9 algorithm-articulated models (#2, 4, 6, 8, 10, 11, and 13-15) were superior than the reference models, all also agreed that the model (# 9) was inferior.

In the second step of the evaluation, the blind was broken. The evaluators were asked to evaluate whether the best ranked algorithm-articulated model was ready for the surgery based on the clinical criteria and by comparing it to the reference model (which was used for the surgery). The results of unblinded evaluation showed that all 3 evaluators agreed that 12 algorithm-articulated models (#2, 4-8, and 10-15) were clinical acceptable and ready for the surgery. In addition, 2 evaluators agreed that 2 of the rest algorithm-generated models (#1 and 3) were ready for surgery, while the other only agreed the model (#3) was ready. Finally, all 3 evaluators agreed that 1 algorithm-generated model (#9) was not ready for the surgery. The problem of the model #9 was mainly due to a significant step between the anterior and right posterior segments which resulted in a right posterior open-bite (upper and lower posterior teeth did not bite together tightly). Fig. 4 showed an example of well algorithm-articulated model (#8) and the unacceptable model #9.

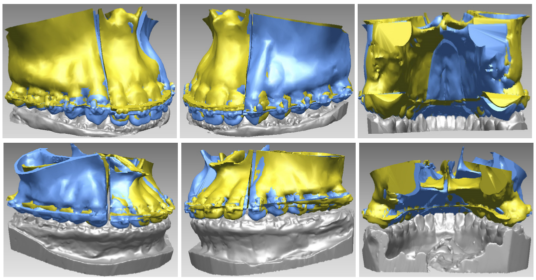
(a)
(b)


**Fig. 4.** Examples of algorithm-generated 3-piece articulation. Yellow: reference model; Blue: experimental model. From left to right: right oblique, left oblique and posterior views. (a) Model #8 - an algorithm-generated 3-piece articulation that is better than the reference model. (b) Model #9 – a clinical unacceptable articulation (the right posterior segment flares out significantly and has a significant posterior open-bite).

### 3.3 Quantitative Validation

To quantitatively validate our method, we computed overjets, overbites, and upper canines deviations (calculated between the upper canines tips and the corresponding lower interstices between the canines and the first premolars). The computations were completed based on the coordinates of the manually digitized two pairs of 4 landmarks on upper and lower models for reference and experimental groups (Fig. 5).

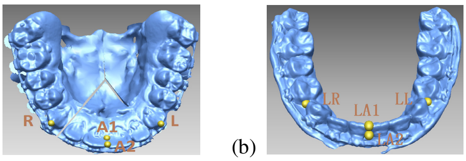
(a)
(b)



**Fig. 5.** Four sets of corresponding landmarks were digitized on the reference upper and lower models. The landmarks on experimental models used the same definition. (a) upper; (b) lower.

The overjets and overbites were computed using the landmark pairs of the upper and lower central dental midlines (A1-A2 and LA1-LA2 for reference; A1'-A2' and LA1'-LA2' for experimental). The deviations for canines were computed using the landmark pairs of the upper canines and the corresponding lower interstices (R-LR and L-LL for reference, and R'-LR' and L'-LL' for experimental). Because our algorithm enforced the perfect alignment of the upper and lower central dental midlines, the midline deviations were therefore not calculated. Means and standard deviations (SD) of these measurements were computed for both reference and the best ranked algorithm-articulated models. The results of the means and SDs are shown in Fig. 6. All of them were clinically acceptable even with the model #9 that was considered clinically not acceptable for surgery. This was because our quantitative evaluation was designed to evaluate overjets and overbites for the anterior segments, and upper canines deviations for the front part of the posterior segments.

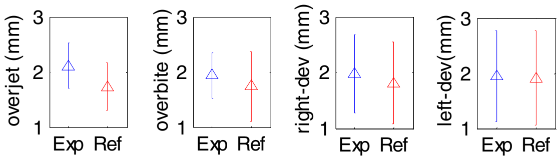



**Fig. 6.** Mean and SD error bars of overjets, overbites, and deviations for canines for reference (Ref) and experimental (Exp) models. From left to right: overjet, overbite, deviation for right canine, and deviation for left canine.

## 4 Discussion and Future Work

Unlike 1-piece dental articulation, it is difficult to reestablish 3-piece articulation even with stone dental casts. Although there are some clinical rules to guide 3-piece articulation, different doctors may have different opinions and habits. Even though each segment is segmentalized at the same location, no articulated 3 pieces of the same patient are the same if they are established by different doctors even with the same clinical rules applied. It becomes even more difficult, if not impossible, to automatically articulate the 3-piece segments in computer. Therefore, it is the authors' believe that the clinical qualitative evaluation is a vital part to the success of the study.

In order to solve above (different opinions among doctors) problems and make the automated 3-piece dental articulation clinically useful, we use a combination of different parameters to articulate the 3 pieces in our MGO approach. Our robust ergodic midline-match algorithm automatically articulates, ranks, and fetches the top 5 optimal positions of the anterior piece. The right and left posterior segments are then aligned to the anterior segment based on its position, and further aligned to the lower teeth using our improved ISMDM algorithm. The results of the validations show an exceptional agreement among the 3 experienced doctors. To our knowledge, this will be the first publication on automatic 3-piece dental articulation.

Currently we are working on optimizing our algorithms for both anterior and posterior alignments. We are also transferring our MATLAB codes into C/CPP. Our goal is to complete the entire 3-piece articulation within a couple of minutes on a regular office PC. In addition, artificial intelligence will be used to summarize and incorporate different doctor's preferences into the algorithm. Furthermore, although we believe our qualitative evaluation is well designed and clinically relevant, we will improve our quantitative evaluation by adding the measurements to detect the maximal intercuspation for the posterior segments. Finally, we will validate our algorithm using partially edentulous models, in which some teeth are missing.

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