

Personalized Orthodontic Accurate Tooth Arrangement System with Complete Teeth Model

Cheng Cheng¹ · Xiaosheng Cheng¹ · Ning Dai¹ · Yi Liu² · Qilei Fan¹ · Yulin Hou² · Xiaotong Jiang¹

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Abstract The accuracy, validity and lack of relation information between dental root and jaw in tooth arrangement are key problems in tooth arrangement technology. This paper aims to describe a newly developed virtual, personalized and accurate tooth arrangement system based on complete information about dental root and skull. Firstly, a feature constraint database of a 3D teeth model is established. Secondly, for computed simulation of tooth movement, the reference planes and lines are defined by the anatomical reference points. The matching mathematical model of teeth pattern and the principle of the specific pose transformation of rigid body are fully utilized. The relation of position between dental root and alveolar bone is considered during the design process. Finally, the relative pose relationships among various teeth are optimized using the object mover, and a personalized therapeutic schedule is formulated. Experimental results show that the virtual tooth arrangement system can arrange abnormal teeth very well and is sufficiently flexible. The relation of position between root and jaw is favorable. This newly developed system is characterized by high-speed processing and quantitative evaluation of the amount of 3D movement of an individual tooth.

Keywords Virtual tooth arrangement · Feature constraint · Slot plane · Dental arch curve · Root plane · Root curve

Introduction

Oral diseases are a kind of common multiple disease. According to the World Health Organization statistics, malocclusion has become one of the three major oral diseases (dental caries, periodontal diseases and malocclusion). For traditional malocclusion treatment, the orthodontic plan mainly relies on a doctor's experience. After the confirmation of a therapeutic plan, a manual tooth arrangement experiment may help the orthodontic doctor estimate the therapeutic process involved in orthodontic treatment as well as inform the patient of possible tooth movement and final treatment effect. The major defects of manual tooth arrangement consist of low efficiency and large consumption of materials.

In recent years, many personalized virtual orthodontic technologies have become available for tooth arrangement and bracket positioning. Generally, they can be divided into the following types:

- (1) Virtual measurement and comparative analysis: The main function of a virtual teeth model lies in the measurement and analysis of the model. One approach considers comparative analysis before and after tooth arrangement. Min-Young Cho et al. [1] superimposed the models through Rapidform, and utilized the 3Txxr program to measure the angles between the teeth and the occlusal plane or midline. Another approach is to compare between the models before and after manual tooth arrangement. Joon Im et al. [2] measured certain values, such as arch length and width of two models through Rapidform for comparison. These two approaches prove

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✉ Ning Dai
dai_ning@nuaa.edu.cn
Cheng Cheng
baojia117@126.com

¹ College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Mailbox 357, 29 Yudao Street, Qinhuai Dist Nanjing 210016, People's Republic of China

² Department of Orthodontics, Peking University School and Hospital of Stomatology, Beijing 100081, People's Republic of China

that the result obtained through virtual tooth arrangement is acceptable compared with that obtained through manual tooth arrangement [3, 4]. However, neither approach accounts for the dental root, which leads to the failure to guarantee the relative position between the dental root and alveolar bone.

- (2) Calculation of tooth movement with mechanical analyses: During orthodontic treatment, tooth movement is the result of the interactions among arch wires, periodontal ligaments and bones. Yukio Kojima and Hisao Fukui [5] adopted finite element analysis to study stress of teeth under arch wires and predict tooth movement. The use of this method while focusing on the movement of a single tooth neglects the stress transfer and displacement change of the whole dentition during orthodontic treatment.
- (3) Simulation of the virtual tooth arrangement process: Simulation of the tooth arrangement process by virtue of the existing software is a type of research [6–11]. Incognito can split the dental model, and the tooth arrangement process can be completed through curve shape adjustment of the dental arch [12, 13]. Orapix 3D can also split the teeth model and arrange the teeth through interactive adjustment of each tooth's position [14–16]. Another type of research relates to the development of the tooth arrangement process simulation in a new system. Based on the drawing principle of the Bonwill-Hawley individual ideal dental arch form, Nobuyoshi Motohashi and Takayuki Kuroda [17] drew the dental arch curve and placed the dental crown models, which had been split on the arch curve in order. In the aforementioned studies, the existing software used or those systems developed by the authors considered only dental crown information, which can possibly result in the dental root outside the alveolar bone.
- (4) Establishment of a complete teeth model: Most orthodontic software still operates only on crown data, and few applications simulate root data with specific

algorithms to simulate tooth movement [18]. This kind of simulation is inadequate for dental procedures. Hong-Tzong Yau et al. [19] reconstructed the dental root CT image into point cloud data through a level set algorithm and utilized iterative closest point algorithm to integrate dental root and dental crown data.

- (5) Tooth-arrangement for complete denture: Yuchun Sun et al. [20], Yong-de Zhang et al. [21–23] and Manabu KANAZAWA et al. [24] significantly contributed to the tooth-arrangement method for complete denture. In particular, Sun and Zhang proposed the principle of Tooth-arrangement. In their research, they considered that the occlusal plane halves the occlusal space, and artificial teeth should be arranged on the alveolar ridge. They also researched the jaw arc configuration and the position relationship of the upper and lower jaw arcs. The curve of the jaw arch and dental arch should be constructed, and an individual tooth is arranged side by side in full denture in close side. Their research provides guidance in the study of tooth-arrangement method.

In conclusion, the existing methods have the following problems. (1) The lack of consideration to the dental root during measurement and analysis may cause the dental root to move outside of the bone cortex during and after treatment. (2) Rough tooth arrangement and inadequate constraints cause low accuracy of tooth arrangement. (3) Low automated tooth arrangement process causes low efficiency of tooth arrangement.

This presentation aims to introduce newly developed software for the computer simulation of the diagnostic cast by demonstrating each clinical processing step. Compared with the manual tooth arrangement, the virtual arrangement does not split the plaster model, and the tooth arrangement process is based on feature constraint driving, without a separate operation for each tooth. With a high automation degree, the tooth arrangement efficiency will be improved accordingly. The relation of position between the dental root and alveolar

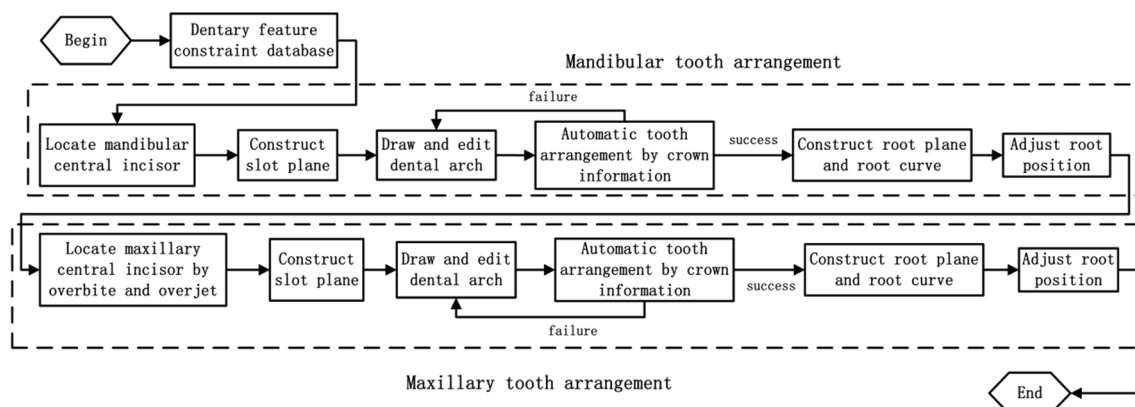


Fig. 1 Pipeline of tooth arrangement algorithm

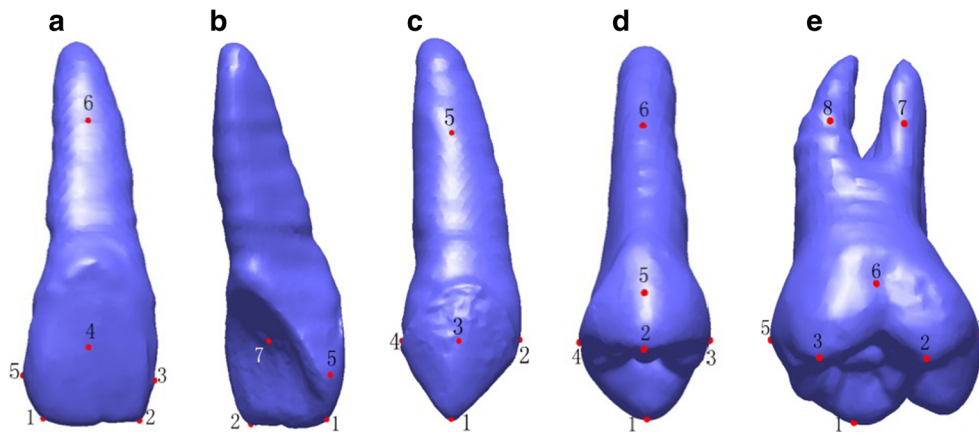


Fig. 2 Definitions of feature points on the models of four kinds of teeth: (a) and (b) Definitions of feature points on the model of the incisor: 1, distal occlusal point; 2, mesial occlusal point; 3, mesial point; 4, bracket point; 5, distal point; 6, root point; 7, fossa point. (c) Definitions of feature points on the model of the canine: 1, cusp point; 2, mesial point; 3, bracket point; 4, distal point; 5, root point. (d) Definitions of feature points on the

model of the premolar: 1, lingual cusp point; 2, buccal cusp point; 3, mesial point; 4, distal point; 5, bracket point; 6, root point. (e) Definitions of feature points on the model of the molar: 1, lingual cusp point; 2, the mesiobuccal cusp tip; 3, the distal buccal cusp tip; 4, mesial point; 5, distal point; 6, bracket point; 7, root point 1; 8, root point 2, the middle point of point 7 and point 8 for root point

bone is integrated into the algorithm design, and the dental crown and root information is comprehensively considered. Therefore, a more appropriate and accurate therapeutic plan is designed to prevent the dental root from protruding out of the alveolar bone, and such problems during the growth process of teeth can be avoided.

Materials and Methods

The dental models in the article were provided by the Department of Orthodontics, School of Stomatology, Peking University. The patient was a young and healthy subject without previous orthodontic or orthopedic treatment histories. The clinical symptom of the patient was mandibular dental crowding. The participant voluntarily joined the study and provided informed consent.

Root information can be extracted from digital imaging and communications in medicine data by the level set method. The

crown data were acquired from plaster models and segmented into individual teeth. The plaster model was positioned according to the referencing model, so the point clouds of root and crown were clustered together exactly. Finally, a full dental model was obtained.

The software to automatically align the individual teeth is newly developed for the computed simulation of diagnostic cast using Visual C++. The automatic tooth arrangement algorithm for computer simulation is demonstrated in Fig. 1.

Construction of Dental Feature Constraint Database

A precise mathematical description of teeth is very difficult because of the irregular shape of teeth. However, from an anatomical perspective, each tooth has some relatively definite feature points. Definitions of feature points should not only embody dental morphological characters fully so that a coordinate system can be structured, but also restrict teeth to

Fig. 3 Feature constraint database

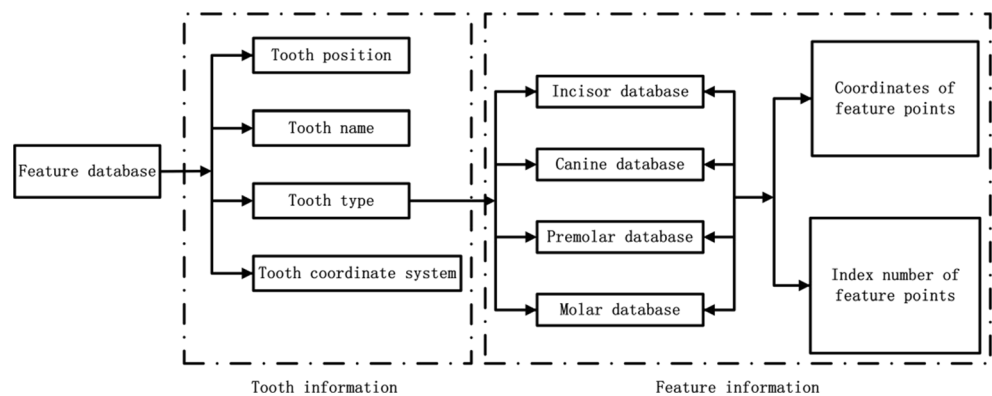
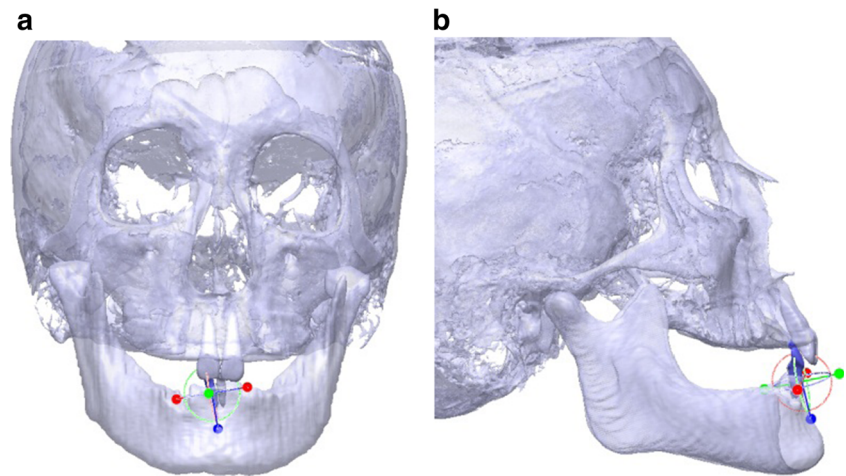


Fig. 4 Translucent mandible and maxilla and central incisors with the object mover: (a) Front view. (b) Left view



arrange teeth. Subsequently, specific positions are formed using a coordinate system. Meanwhile, the boundary conditions of dental restriction comprise feature points. Feature points are marked by an orthodontist.

Teeth are divided into four main groups based on function and characteristics: incisor, canine, premolar and molar. Figure 2 shows the definitions of feature points of four kinds of teeth.

Feature constraints of each tooth constitute tooth position, tooth type, coordinates of feature points and index number of feature points. Feature constraints of all teeth are also included into the feature constraint database, as shown in Fig. 3.

Tooth Arrangement Based on Feature Constraint Driving

Mandibular Tooth Arrangement

Step 1 *Location of mandibular central incisors.* An object mover function is developed to rotate the object about three axis and slide the object through space along the three axis. With mandible and maxilla models, the positions and orientation of mandibular central incisors are adjusted interactively using the

object mover. This step is based on the experience of doctors, as shown in Fig. 4.

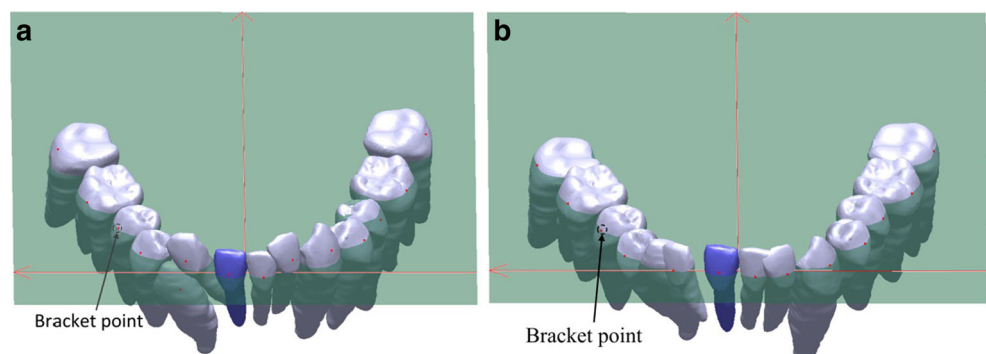
Step 2 *Adjustment of initial teeth positions.* The important slot plane is constructed using the midpoint of the bracket points of mandibular central incisors and bilateral mandibular first molars. The normal component N_p of the slot plane is defined. Positions and pose of mandibular teeth are adjusted such that the teeth bracket points are on the slot plane, and the long teeth axes are superposed with N_p , as shown in Fig. 5.

Step 3 *Construction of dental arch curve.* The projection points in the midpoint of the mesial points of mandibular central incisors, the cusp points of bilateral mandibular canines and the distal points of bilateral mandibular first molars are defined as model points. The dental arch curve is simulated by B-spline curve (Eq. (1)).

$$p(t) = \sum_{i=0}^n Q_i N_{i,k}(t), \quad t \in [0, 1] \quad (1)$$

In the formulae, $p(t)$ refers to model point, Q_i is control point, t is node value, n is number of control

Fig. 5 Relationship between slot plane and teeth: (a) Original position. (b) Teeth positions along the plane normal component are adjusted to situate bracket points on the slot plane



points and $N_{i,k}(t)$ is k-degree B-spline basis function (Eqs. (2) and (3)).

$$N_{i,1}(t) = \begin{cases} 1, & t_i \leq t \leq t_{i+1} \\ 0, & \text{else} \end{cases} \quad (2)$$

$$N_{i,k}(t) = \frac{(t-t_i)N_{i,k-1}(t)}{t_{i+k-1}-t_i} + \frac{(t_{i+k}-t)N_{i+1,k-1}(t)}{t_{i+k}-t_{i+1}} \quad (3)$$

Step 4 Automatic tooth arrangement. B-spline curve is constructed with the control points reversed by five model points. B-spline curve is edited according to expertise so that a suitable arch can be obtained, as shown in Fig. 6. Based on tooth width, the position of the corresponding string of teeth on the arch is obtained by iterative calculation. Subsequently, the teeth can

be automatically arranged. In the figure, (x_i, y_i) is the projection of the distal point of tooth on the slot plane, and (x_{i-1}, y_{i-1}) is the projection of the mesial point on the slot plane. Location information of each tooth can be defined as $T_i = \{T_{\text{mesial}}, T_{\text{distal}}\}$ ($i=1, 2, \dots, N$). T_i is the location information of the tooth, T_{mesial} is the location of the mesial point, T_{distal} is the location of the distal point and N is the number of teeth. Fig. 7 shows the result of tooth arrangement. According to the orthodontist, the dental arch curve can be adjusted by moving the control points on the slot plane to establish the optimum occlusal relationship. The result of tooth arrangement changes accordingly, as shown in Fig. 8. Written in pseudo-code, the iterative algorithm is shown as follows:

Algorithm 1: Calculate new mesial points and distal points.

Input: Array of teeth positions T; Array of arch P, stored as array of points; Origin of arch coordinate system O.

Output: Array of new mesial points and distal points N.

foreach central incisor $q \in T$ **do**

```

    N_mesial ← O
    foreach  $p \in P$  do
        if length  $L_1(N_{\text{mesial}}, p) = L_2(q_{\text{mesial}}, q_{\text{distal}})$  then
            N_distal ← p
    
```

foreach non central incisor $r \in T$ **do**

```

    r' ← r-1
    N_mesial ← r'_distal
    foreach  $p \in P$  do
        if length  $L_1(N_{\text{mesial}}, p) = L_2(r_{\text{mesial}}, r_{\text{distal}})$  then
            N_distal ← p
    
```

return N

Step 5 Construction of root plane and root curve. The above method used dental crown information only, and teeth roots cannot be guaranteed in the alveolar bone. According to experts, the root plane is parallel to the slot plane, and the two planes are 15 mm apart. The projections of mandibular teeth root points are designed as

model points $p(t)$. Thereafter, the root curve is constructed by the B-spline curve, as shown in Fig. 9.

Step 6 Modification of root position. The roots should be guaranteed in the alveolar bone, and the above constraints are always maintained. Using the line between T_{mesial} and T_{distal} as the axis, the tooth can be

Fig. 6 Dental arch and dental model: (a) Dental arch and the positions of teeth before arrangement; (b) Location of teeth and dental arch

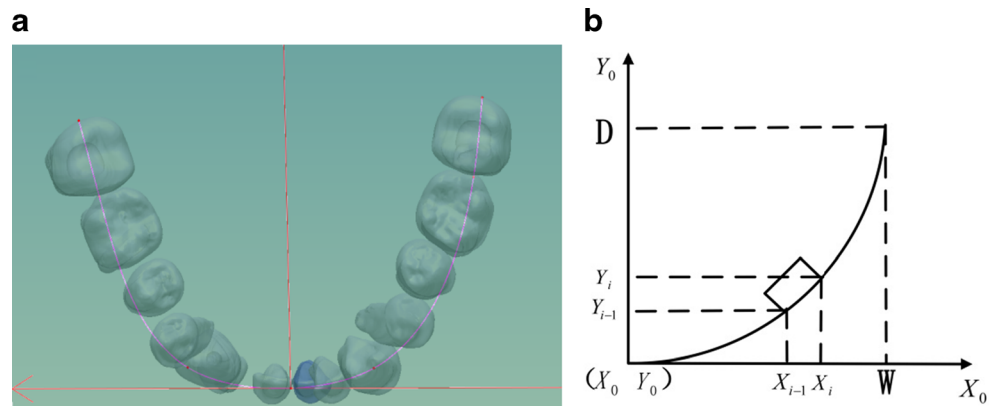
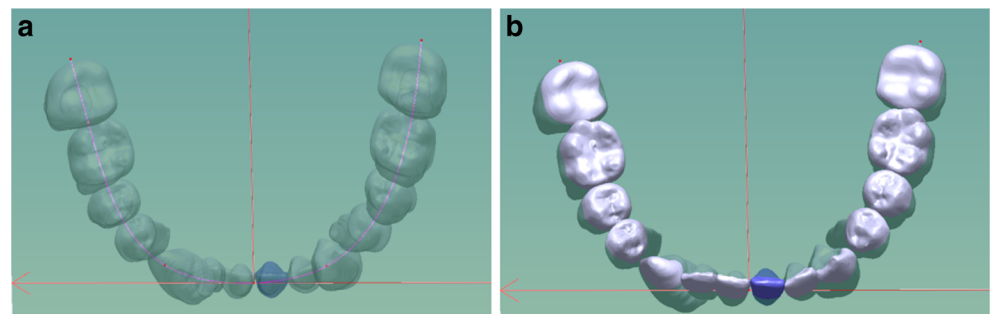


Fig. 7 Location of teeth and dental arch after tooth arrangement: (a) Translucent model; (b) Opaque model



rotated about the axis by moving the point $p(t)$ to ensure root in the alveolar bone, and the root curve is edited in real time simultaneously. Mandibular teeth are completely arranged after editing the teeth roots. The middle plane is then established so that the position information of mandibular central incisors is delivered to the maxillary central incisors (Fig. 10).

Maxillary Tooth Arrangement

Step 1 *Location of maxillary central incisors.* The positions of maxillary central incisors are adjusted relative to the middle plane so that T_{mesial} is on the middle plane. According to overbite and overjet relation, the positions

of bilateral maxillary central incisors are confirmed using the projections of mesial occlusal points of mandibular central incisors, fossa points and mesial occlusal points of maxillary central incisors.

Step 2 *Adjustment of initial maxillary teeth positions.* Similar to mandibular tooth arrangement, the maxillary slot plane is constructed. The positions and pose of maxillary teeth are adjusted so that the bracket points of teeth are on the slot plane, and the long teeth axes are superposed with the normal slot plane component.

Step 3 *Construction of maxillary dental arch curve and arrangement of maxillary teeth.* The occlusion problem must be considered. By projecting the result of expanding mandibular dental arch by 2 mm along

Fig. 8 Tooth arrangement after adjusting the arch curve: (a) Adjusted dental arch curve; (b) Result of tooth arrangement

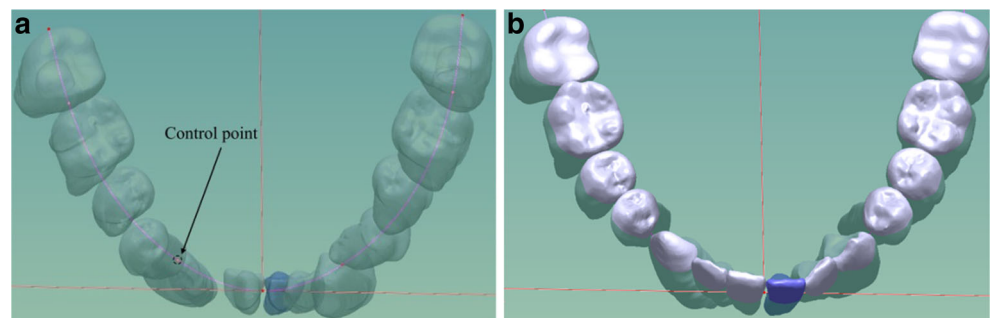
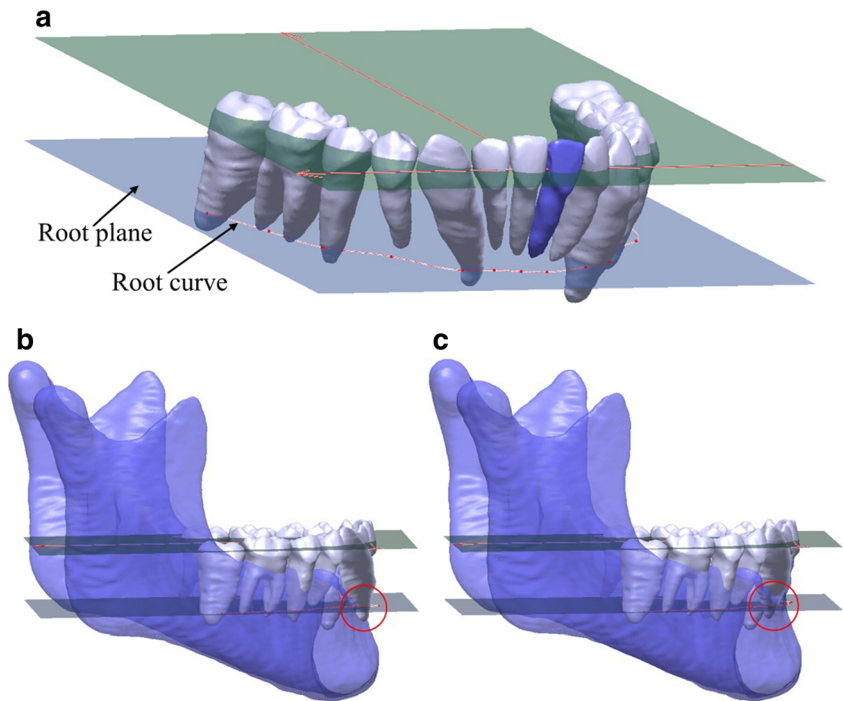


Fig. 9 Root plane, root curve and tooth arrangement with root information: (a) Root plane and root curve. (b) Unadjusted tooth root. (c) Adjusted tooth root



its normal direction onto the maxillary slot plane, the maxillary dental arch curve is constructed (Fig. 11).

Written in pseudo-code, the maxillary arch algorithm is shown below:

Algorithm 2: Calculate maxillary arch

Input: Array of mandibular arch L, stored as array of points; Normal direction of maxillary slot plane N_p .

Output: Array of maxillary U.

foreach $p_i \in L$ **do**

$D \leftarrow p_i - p_{i-1}$

$B \leftarrow D \times N_p$

$U \leftarrow 2 \cdot B$

return U

Step 4 *Modification of root position.* The construction of the maxillary root plane and root curve is the same as the mandibular tooth arrangement. Root curve and pose of maxillary teeth are edited in real time by moving the model points. Consequently, maxillary tooth arrangement is accomplished.

Experimental Results

The visual data show that the tooth arrangement algorithm can achieve better result (Figs. 12 and 13). Combining the translucent skull models, the parts of all teeth roots can be observed in the alveolar bone (Fig. 14). The total tooth arrangement time is about 10 min.

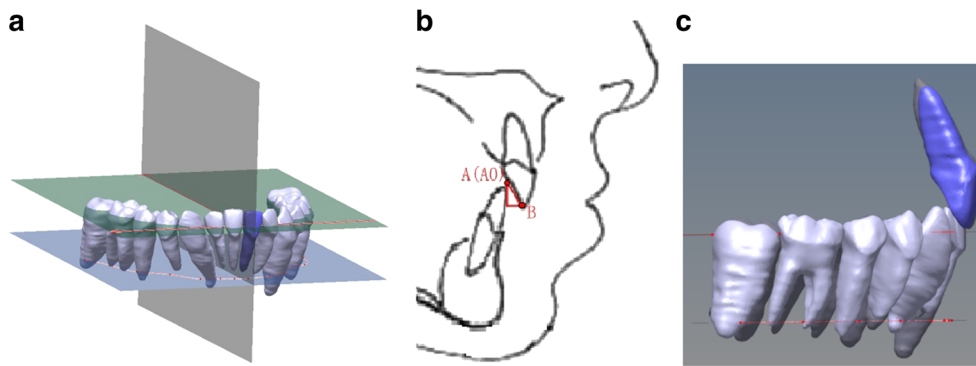


Fig. 10 Orientation of maxillary central incisors: (a) Situation and posture information of mandibular central incisors delivered by the middle plane. (b) Overjet and overbite relation (A is the mesial occlusal

point of right mandibular central incisor, A0 is the fossa point of right maxillary central incisor, B is the mesial occlusal point of right maxillary central incisor). (c) Maxillary central incisor model after adjustment

Fig. 11 Set up of maxillary teeth: (a) Maxillary dental arch and translucent dental model. (b) Tooth arrangement with root information

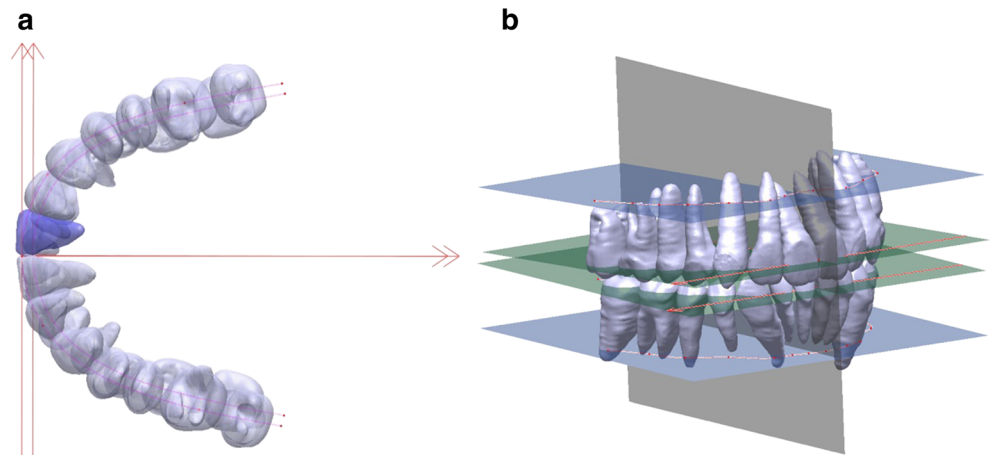


Fig. 12 Process of maxillary tooth arrangement: (a) Original teeth. (b) After adjusting the location of the maxillary central incisors. (c) After adjusting the initial pose of maxillary teeth. (d) After arranging the maxillary teeth

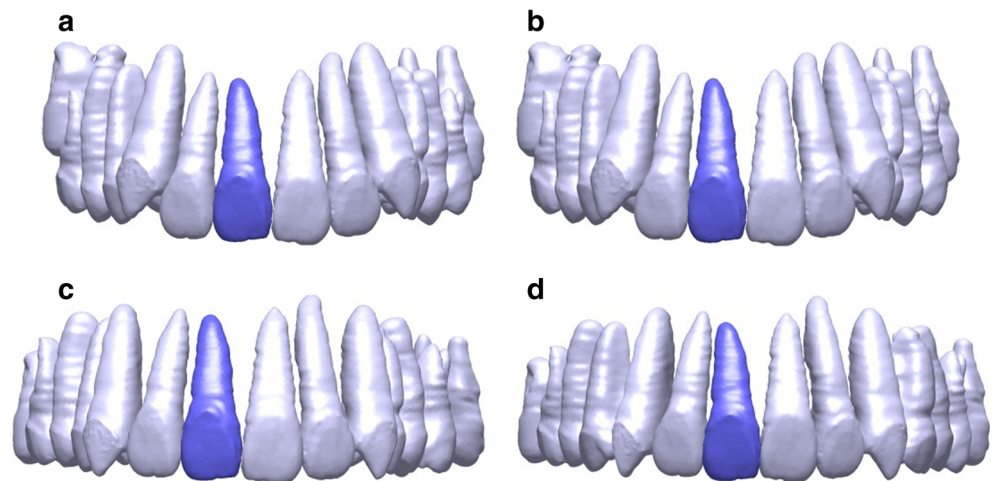


Fig. 13 Process of mandibular tooth arrangement: (a) Original teeth. (b) After adjusting the location of the mandibular central incisors. (c) After adjusting the initial pose of the mandibular teeth. (d) After arranging the mandibular teeth

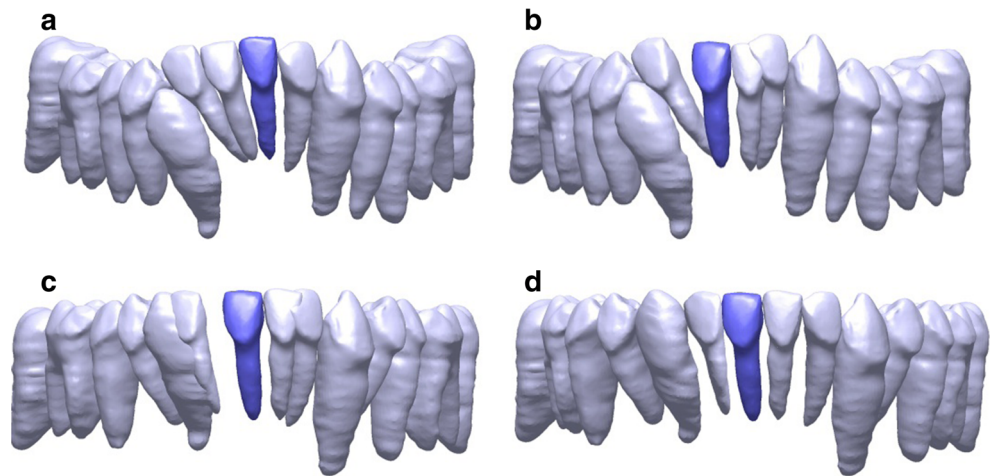
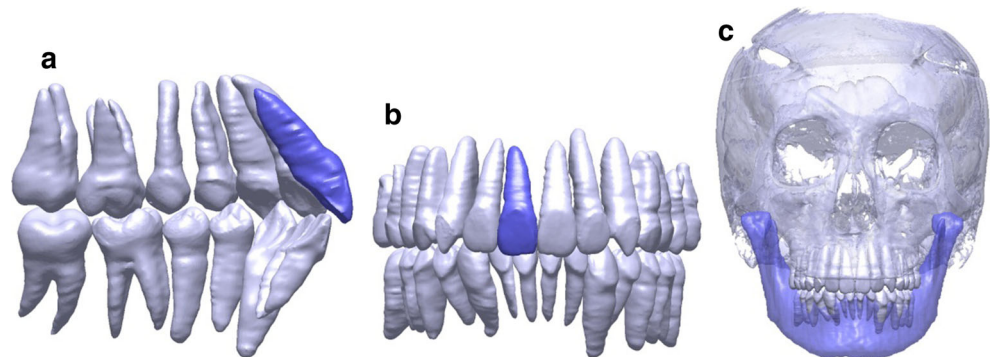


Fig. 14 Result of tooth arrangement: (a) Occlusal relationship. (b) Dentition after tooth arrangement. (c) Dentition and translucent skulls



Discussion

The relative position between teeth roots and alveolar bone, as well as the difference between manual and virtual setup models, is quantitatively analyzed through linear measurement.

Analysis of Arch Form

Figure 15 describes the reference lines and landmarks for the linear measurements, and Table 1 shows the measurement results.

The measurement results of the manual setup model closely resemble that of the virtual setup model. Results show that

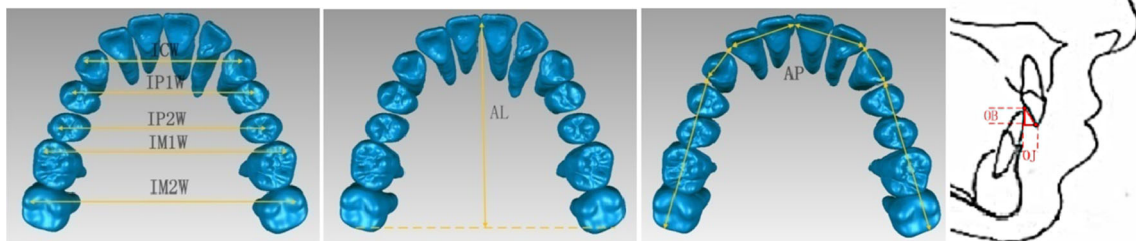


Fig. 15 Measurement values for arch dimensions: ICW, intercanine width, distance between the cusp tips of the right and left canines; IP1W, interfirst premolar width, distance between the cusp tips of the right and left first premolars; IP2W, intersecond premolar width, distance between the cusp tips of the right and left second premolars; IM1W, interfirst molar width, distance between the mesiobuccal cusp tips of the right and left first molars; IM2W, intersecond molar width, distance between the mesiobuccal cusp tips of the right and left second

molars; AL, arch length, distance between the midpoint of the occlusal point of the central incisor and the midpoint of the distal point of the second molars; AP, arch perimeter, perimeter between the distal points of the right and left second molars; OJ, overjet, the horizontal distance between the midpoint of the upper and lower central incisors' occlusal points; OB, overbite, the vertical distance between the midpoint of the upper and lower central incisors' occlusal points

Table 1 Comparison of arch dimensions between manual and virtual setups

		Manual setup(mm)	Virtual setup(mm)	Deviation(%)
Maxillary	ICW	38.423	38.317	0.276
	IP1W	46.574	45.979	1.278
	IP2W	52.370	51.993	0.72
	IM1W	58.221	58.89	-1.15
	IM2W	64.246	65.154	1.413
	AL	49.891	49.46	0.864
	AP	126.228	124.512	1.359
	Mandibular	ICW	28.273	28.6
IP1W		36.867	36.226	1.739
IP2W		45.999	45.112	1.928
IM1W		51.182	50.81	0.727
IM2W		56.984	55.908	1.888
AL		45.846	45.664	0.397
AP		117.197	115.711	1.268
OB		1.41	1.57	-11.348

Deviation, use manual setup model as the reference

the arch width of manual setup model is wider than that of the virtual setup model at about 0.1-0.9 mm. The arch length of the manual setup model is 0.3 % longer than that of the virtual setup model. The arch perimeter of the manual setup model is 1.2 % longer than that of the virtual setup model. Thus, the virtual setup model is tighter than the manual setup model.

Analysis of the Positions of Teeth Roots

An innovation in this study is the application of a complete dental model with information of teeth roots to tooth arrangement, which is hardly reported in the literature. In the course of measuring the relative position between teeth roots and

Table 2 Root tip distance: the minimum distance between root tip and alveolar bone

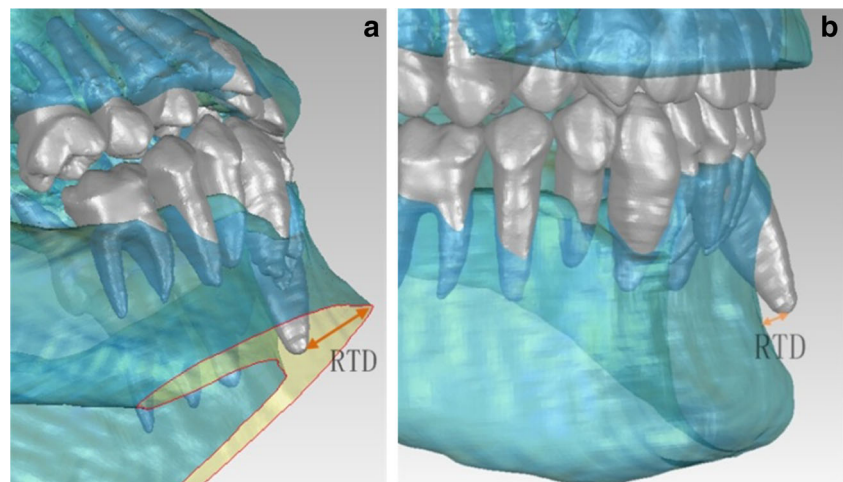
		Right side(mm)	Left side(mm)
Maxillary	U1	+8.184	+7.655
	U2	+4.998	+4.231
	U3	+3.505	+2.561
	U4	+2.917	+3.915
	U5	+3.849	+4.19
	U6	+3.572	+4.501
	U7	+7.135	+5.934
Mandibular	L1	+3.85	+3.025
	L2	+4.1	+4.544
	L3	+4.428	+3.965
	L4	+7.286	+6.588
	L5	+4.87	+4.185
	L6	+4.68	+5.145
	L7	+6.218	+7.414

U1, upper central incisor; U2, upper lateral incisor; U3, upper canine; U4, upper first premolar; U5, upper second premolar; U6, upper first molar; U7, upper second molar; L1, lower central incisor; L2, lower lateral incisor; L3, lower canine; L4, lower first premolar; L5, lower second premolar; L6, lower first molar; L7, lower second molar; "+" means root tip in alveolar bone

alveolar bone, the concept of root tip distance is introduced. Root tip distance is the minimum distance from the root tip to alveolar bone (Fig. 16). The root tip distance is positive when the root tip is in the alveolar bone, but negative when the root tip is outside the alveolar bone (Table 2).

Results show that the root tips of the virtual setup model are all in the alveolar bone. Root tip distances of bilateral maxillary central incisors are relatively large. Bilateral maxillary central incisors incline their roots towards the skull. The present tooth arrangement methods are mainly about crown information, whereas root information is not considered. Thus, the negative effect of these methods is that teeth roots are outside

Fig. 16 Root tip distance (RTD) is the minimum distance between the root tip and alveolar bone: (a) Root tip in the alveolar bone, "+" distance. (b) Root tip outside the alveolar bone, "-" distance



of the alveolar bone. This phenomenon tends to be overlooked during therapy.

Efficiency Analysis

In comprehensive consideration of information of the crown and root of the dental model, the tooth arrangement method designed in this paper realizes automation of tooth arrangement. The total tooth arrangement time is 10 min, and manual setup takes about one week. Without handling plaster casts, this method does not only increase the tooth arrangement efficiency, but also lowers cost. With rapid prototyping technology, arch wire and brackets can be rapidly manufactured simultaneously.

Conclusions

Orthodontic treatment features complex tooth arrangement, long treatment cycle and unpredictable outcome. However, in traditional orthodontic treatment, dentists consider only the relationship among dental crowns and neglect the root condition, which might result in the hidden danger of unpredictable long-term treatment. Based on the complete dental model containing information on teeth roots, this paper proposes a novel tooth arrangement system that is applied in an orthodontic treatment plan to design a comprehensive tooth arrangement algorithm with automated teeth crown contact and teeth root pose. This system has several advantages. (1) The system is characterized by highly efficient tooth arrangement. This method of tooth arrangement can achieve automated tooth arrangement, with an operation time of about 10 min. (2) The system considers the positions of teeth roots, thereby avoiding the hidden danger that teeth roots might move to outside of the cortex in or after treatment. (3) The system has a stable quality of tooth arrangement, and the outcome is similar to that of manual tooth arrangement.

However, some problems still exist for this system; for example, the automatic level should be raised. In future studies, many aspects, such as the feature points, should be automatically flagged for the dental feature constraint database, and the relationship between root tip and alveolar bone must be automatically detected.

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Conflict of Interest The author(s) declare that they have no competing interests.

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