Digital expression and interactive adjustment method of personalized orthodontic archwire for robotic bending

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Abstract
The robotic archwire bending technology has been used clinically to free orthodontic doctors from the heavy labor because of the improvement of the digital medical technology, and the digital expression of orthodontic archwire is necessary to realize the robotic archwire bending. Because of the differences between the human tooth arrangement and the difficulty of archwire shape design, it is difficult to realize the digital expression of orthodontic archwire. A method for the digital expression and interactive adjustment of personalized orthodontic archwire is presented in this paper. The straight section and the transitional section of the brackets are defined according to the reference points of the brackets. The transitional sections of the brackets are built by the mathematical model of Cubic Bezier curve. The process of handmade archwire bending, the method of discretization and combination are considered in the establishment of the mathematical model and model library about special function arch curve. The ways of the adjustment of the straight sections, the deformation of the transitional section shape, the selections of the position and type of special function arch curve are used in the study of the method for the digital expression and interactive adjustment of personalized orthodontic archwire. The interactive adjustment software is designed by the LABVIEW software. The archwire bending experiment is carried out, the error rate of the bent archwire ranged between 1.1% and 6.7% which proves the digital expression and interactive adjustment method of personalized orthodontic archwire for robotic bending is feasible and effective.

Keywords: Digital expression, Personalized orthodontic archwire, Archwire modeling, Interactive adjustment, Robotic bending

1. Introduction

Malocclusion is regarded as one of the three oral diseases according to the research of the World Health Organization (Cheng et al., 2015; Stewart et al., 2001; Wu., 2018). Digital forming technology is used more and more extensively in the modern field of orthodontics to treat the malocclusion (Schmidt et al., 2018), such as dental 3D digital reconstruction technology, digitalized brackets indirect bonding technology and orthodontics archwire bending robotic technology (Castro et al., 2018). Clinically, orthodontic archwire-assisted forming equipment and orthodontic archwire bending machines have been used to bend orthodontic archwires (Jiang et al., 2018), such as the SureSmile system. However, the variation of human teeth is not only related to race and gender, but also the difference of individual development. In order to offer better compensation for the differences between individual dentition, the best way is to develop a personalized orthodontic appliance for each individual. And personalized orthodontic archwire bending needs personalized archwire shape design. The customized archwire shape is the basis of orthodontics archwire bending. And the existing orthodontic archwire forming method restricts personalized archwire shape design (Yang et al., 2015).

Domestic and foreign scholars have studied the design of orthodontics archwire. Gilbert et al used the mouth 2D image to design orthodontic archwire in XY plane. They developed a LAMDA system (Lingual Archwire Manufacturing and Design Aid) of lingual treatment that can be used in the customized orthodontic archwire design
(Liu et al., 2012). Using cone beam CT scanning for teeth, Tharso I. Smith et al got initial tooth column scanning model. They used SureSmile system to generate personalized orthodontic archwire. They set up the target model and carried out the simulation. Their aim is to evaluate whether there is a difference between the tilt and twist of the teeth and treatment results. The difference between the target model and the clinical results are within ±2.5° (Gilbert, 2011). R Mullerhartwich et al used SureSmile to make comparison and analysis between virtual planning teeth mobile location of 26 patients and the actual teeth mobile location after orthodontic treatment. The method of virtual matching is adopted in this process. The results show that the average deviation of three planes is 0.1900-0.2102mm, and the mean deviation from three directions is 1.70-3.04°. And correction accuracy from central incisor to molar is decreasing gradually. And the correction accuracy of the central incisor is the highest (Tharon et al., 2015). Zhang Lin et al reviewed the characteristics of 5 kinds of ideal dental arch fitting curve, such as Bonwill-Hawlay figure, the Catenary curve, Brader arch, Vari–Simplex arch and Roth arch. Then they analyzed advantages and disadvantages of 6 kinds of personalized dental arch fitting methods such as mathematical method, the Euclidean distance matrix analysis method, the finite element analysis, four point restoration method, the two point forming method, and triangular mesh on dental archwire of the dental arch model semi-automatic detection method. From such analysis, the existing digital design and fitting of orthodontics is two-dimensional. And fitting arch curve is not suitable for each patient (Müllerhartwich et al., 2016). Zhang Wenjun et al conducted 3D modeling of orthodontic archwire, linear segmentation and fitting of three-dimensional model. They developed 3D virtual design software and designed a virtual archwire bending system (Zhang, 2012). Dai Ning et al put forward a kind of adjustment method of virtual teeth arrangement and virtual occlusal surface of complete denture. They developed the virtual teeth arrangement system. The customized bracket shape and assisted-bonding tray based on neat rows of teeth arrangement was designed. The personalized orthodontic archwire was designed according to the position of the archwire slot on the bracket (Zhang, 2013 and Fan et al., 2015).

The robotic archwire bending technology has been used clinically to free orthodontic doctors from the heavy labor because of the improvement of the digital medical technology, and the digital expression of orthodontic archwire is necessary to realize the robotic archwire bending. The purpose of this paper is to study the digital expression of the first sequence of personalized orthodontic archwire and the second sequence special arch function, and set up parameterized mathematical model to realize the robotic archwire bending. On the basis of that, the research of interaction adjustment method is carried out (Cheng et al., 2015). At the same time, model foundation is established to realize the digitalization and personalization of orthodontic archwire and the study of the forming method for the bending of the second sequence of the orthodontic archwire.

2. Modeling analysis of parametric expression of orthodontic archwire curve

A relatively complete system has been established in orthodontics. The fixed orthodontic technique is used in this system to carry out the treatment of malocclusion that is patients wearing orthodontic appliances. Orthodontic appliance is composed of brackets and orthodontic archwire. The bracket with metal grid or etching plate, through the adhesive bonding tightly in a specific location of facing, is used to fix archwire. Forming orthodontic archwire gets stuck in bracket by ligation wire. Various orthodontic force is exerted on tooth through the bracket by the archwire. 3D movement of the tooth is controlled by the orthodontic force to realize orthodontic treatment. When bending the orthodontic archwire, doctors need a large number of clinical compensation with standard arch according to patients’ tooth arrangement. The application of personalized bracket and its bonding position are affected by the archwire shape design. Therefore, the archwire shape is not only limited to standard geometry. It can also be very irregular.

Due to the limitation of the shape of bracket groove, archwire usually contacts bracket with straight section. The archwire forms between different brackets are different because individual differences exist in shape and position of two adjacent teeth. During the manual bending process of the orthodontic archwire, the tag position is firstly marked as shown in Fig.1. And another important point called experience point is marked by measuring a length of the straight section of orthodontic archwire on both sides of the tag position. This length is decided according to doctor’s experience. The end of this straight section is the experience point. The tag position is also the bending point or special arch curve insertion point in the process of orthodontic archwire bending.
During the process of clinical oral orthodontic treatment, firstly, doctors need to pull the maxillary and four fangs of jaw, and then carry out orthodontic treatment. Commonly, ordinary people have 28 teeth or 32 teeth. Therefore, in the process of correction of jaw deformity, the only need of orthodontic appliance is to adjust the space position and posture of 28 teeth. In the modeling process, only the arch position information of 28 teeth (including the 14 on the maxillary, the 14 tooth on the mandibular) need to be established. There are two bending points on left and right sides of each tooth adhesion brackets. So the maxillary and mandibular arch curve digital forming process requires 28 reference points of the coordinate information as the basic information. The midpoint on the left and right sides of the bracket groove is the reference point, as shown in Fig. 2. It is also the original data points which is provided by orthodontic doctors for us.

According to the patient’s dental deformity, orthodontic doctors add a special function curve between the two brackets to apply different orthodontic force. For example, there are two different kinds of the box-shaped loop. One is the vertical box-shaped loop for the depression and extension of the teeth. The other one is the positive axis of the box-shaped loop which is used to correct individual teeth tilt (Bai, 2016). The shape of the special function curve is complex and diverse, so it is difficult to express with accurate mathematical expression. Therefore, the manual archwire bending needs to be considered. The mathematical model of the special function curve of the orthodontic archwire is expressed by the combination of discrete straight line and arc, and the expression is applied to the bending motion of the robot more easily (Jiang et al., 2015; Liu, 2013; Luo, 2010; Zhang et al., 2014).

3. Analysis of method for the interactive adjustment of orthodontic archwire curve

According to the data of the maxillary teeth provided by the orthodontists, the marking and bending method of the bending point, the special arcuate curve insertion point of the orthodontic doctor, the orthodontic arch curve are discretized into 14 straight sections and 13 transitional sections. The discrete rear arcuate curve plane projection is shown in Fig. 3. The solid line is the straight section of the orthodontic archwire. When the position marking is performed, the lengths extending along the both sides of the straight section are used as the compensation value. And the compensation value is added on both sides of the straight section. The dotted line is the transitional section. According to the characteristics of the orthodontic archwire, there is no connection between the curves, so there is no influence on the control point of the Bezier curve and the B-spline curve. Bezier curve is more in line with the requirements because the endpoints should be the starting points of the transitional section, and the shape of the curve should be controlled. The shape of the Bezier curve is designed by changing the parameter value, and the Bezier curve expression is simpler than the B-spline curve. Therefore, the transitional section is based on mathematical model of the cubic Bezier curve.

The straight sections and the transitional sections are combined into the arch shape of the orthodontic archwire curve. As is shown in Fig. 3, the arch shape is closely related to the arch shape after the process of the orthodontic treatment. It can only be designed by the orthodontist based on the principle of distortion. Therefore, orthodontic archwire shape can be obtained through the connection between the straight sections and the transitional section.
according to the patient’s maxillary tooth data. This process is established on the patient’s arch curve before the orthodontic treatment. Orthodontic doctors change the space position of the straight section of the brackets, and change the arch shape of orthodontic archwire curve to achieve the purpose of orthodontic archwire personalized design. As is shown in Fig. 4, according to the teeth in the correction process, the features of tooth movement, such as the tooth plane lateral translation, the translation of the plane perpendicular to the tooth surface, the rotation of the tooth surface, and the displacement of the tooth movement and small tooth rotation angle. Therefore, the position of the straight section is adjusted using the way of straight section moving perpendicularly to the surface and rotating around the two ends of the brackets.

![Fig. 3 Digital expression of dental arch curve](image1)

![Fig. 4 Adjusted expression of dental arch curve](image2)

The special function curve in the orthodontic archwire curve is a curve with special shape. As shown in Fig. 5, some widely used orthodontic archwire includes open vertical loop, tear loop, enclosed tear loop and the box loop. The shape of the curve is complex. So that the special function curve of each orthodontic archwire curve should be parameterized. The shape of these archwire can be described by its height \( w \), width \( u \), and the diameter \( \varphi \) of the enclosed part. The establishment of mathematical model database of special function curve is necessary. After that, in the process of interactive adjustment, the orthodontist just needs to select the location and the type of the special function arch curve according to the needs of the treatment plan.

![Fig. 5 Special function arch curve](image3)

### 3.1 Mathematical model of interactive adjustment of orthodontic arch wire curve

1. Patient’s data refers to orthodontic archwire forming datum point. It is the basics of personalized orthodontic archwire curve forming. In the process of insertion, the orthodontic doctor needs to select the patient’s data and import it into the orthodontic curve forming system. Take the maxillary 14 teeth, for example, the patient’s maxillary data consists of 28 space points. Two data points on each tooth forming the space line is the straight section. The two adjacent straight sections are connected through a transitional curve which is called a transitional section. Using the international standard of the FDI tooth recording method, the tooth’s corresponding straight section is expressed by its position, and the transitional section is expressed by two adjacent teeth’ position. The order of the straight sections of the brackets is recorded from the right to the left by the dentist's position, and the order is 18, ..., 11, 21, ... 28 using the FDI tooth recording method. Let \( i \) represent the \( i \)-th tooth in the tooth order of the patient \((i = 0, 1, ..., 13)\), so \( i \) of tooth position 18 is 0. \((x_0, y_0, z_0)\) and \((x_1, y_1, z_1)\) are the tooth coordinates of the two points on the tooth position 18. The \( i \) of tooth position 21 is 7, and the tooth coordinates of the two points on the tooth position 21 are \((x_{14}, y_{14}, z_{14})\) and \((x_{15}, y_{15}, z_{15})\). The coordinates of the two points on the \( 1 \)-th tooth are \((x_{2i}, y_{2i}, z_{2i})\) and \((x_{2i+1}, y_{2i+1}, z_{2i+1})\).

2. The setting of the compensation value is to set the length extending along the both sides of the straight section. The mathematical model of the straight section is built on the orthodontic archwire data points. In order to realize the better interaction, the way compensation value added on both sides of the straight section is familiar with the
orthodontic doctor: mesio-middle compensation value $a_t$ and distal-middle compensation value $b_t$. $a_t$ and $b_t$ are the lengths extending along the both sides of the straight section. The mathematical model is as follows.

$$\begin{align}
\left( l_i, l'_i,l''_i \right) &= \frac{(x_{2i-1} - x_{2i}, y_{2i-1} - y_{2i}, z_{2i-1} - z_{2i})}{\sqrt{(x_{2i-1} - x_{2i})^2 + (y_{2i-1} - y_{2i})^2 + (z_{2i-1} - z_{2i})^2}} \\
&= \left( \frac{y_{2i} - b_i \cdot y_{2i} - a_i \cdot z_{2i} - l_i \cdot b_i}{y_{2i} - l_i \cdot a_i}, \frac{x_{2i} - l_i \cdot b_i, y_{2i}, z_{2i} - l_i \cdot b_i}{z_{2i} - l_i \cdot z_{2i} - l_i \cdot b_i}, \frac{x_{2i} - l_i \cdot b_i, y_{2i}, z_{2i} - l_i \cdot b_i}{x_{2i} - l_i \cdot b_i, y_{2i}, z_{2i} - l_i \cdot b_i} \right) \\
&= \left( \frac{x_{2i} - l_i \cdot a_i, y_{2i} - l_i \cdot b_i, z_{2i} - l_i \cdot a_i}{x_{2i} - l_i \cdot a_i, y_{2i} - l_i \cdot b_i, z_{2i} - l_i \cdot a_i} \right)
\end{align}$$

(1)

(3) The setting of the transitional section is to set the value of the proportional parameter to adjust the position of the two control points of the Cubic Bezier curve. The shape of the transitional section can be changed by the control points. The Cubic Bezier curve with two starting points and two control points is selected in the transitional section of the orthodontic archwire curve. The expression can be simplified as:

$$N(t) = N_0 \cdot (1-t)^3 + 3 \cdot N_1 \cdot t \cdot (1-t)^2 + 3 \cdot N_2 \cdot t^2 \cdot (1-t) + N_3 \cdot t^3$$

(2)

Where, $N_0, N_1, N_2$, and $N_3$ represent the control points of the Cubic Bezier curve.

A transitional section is composed of two adjacent brackets, and the control points $N_0, N_3$ are the starting points of the transitional section. $N_0, N_3$ are also the end of the straight section after adding the compensation value. The $x$ and $y$ values of the intersecting points of the two adjacent brackets are plotted into the spatial straight lines of each segment, and their coordinates in the Z-axis direction are obtained to form an intermediate point $(x, y, z)$. The intermediate point connects with the end point of the corresponding straight section. The connected line is divided by a certain proportion. The distribution points are the two control points $N_1, N_2$. $(X_0, Y_0)$ is the intersection of the straight line of the adjacent bracket line on the XY plane projection. $(X_0, Y_0, Z_0)$ and $(X_6, Y_6, Z_2)$ are obtained by substituting the intersection point $(X_0, Y_0)$ into the space linear equations of the straight sections. So the four control points of the transitional section are as follows:

$$\begin{align}
N_0 &= (X_{2i-1}, Y_{2i-1}, Z_{2i-1}) \\
N_1 &= (X_{2i-1}, Y_{2i-1}, Z_{2i-1}) + e_1 \cdot (X_0 - X_{2i-1}, Y_0 - Y_{2i-1}), Z_{2i-1} + e_1 \cdot (Z_0 - Z_{2i-1}) \\
N_2 &= (X_{2i+1} - f_1 \cdot (X_{2i+1} - X_0), Y_{2i+1} - f_1 \cdot (Y_{2i+1} - Y_0), Z_{2i+1} - f_1 \cdot (Z_0 - Z_{2i+1}) \\
N_3 &= (X_{2i+1}, Y_{2i+1}, Z_{2i+1})
\end{align}$$

(3)

Where, $e_i, f_i$ are the proportional parameters. The shape of the convex closure is adjusted through the Bezier curve control points $N_1, N_2$. And the Bezier curve control points $N_1, N_2$ can be changed through $e_i$ and $f_i$. This method can adapt the transition curve segment to a variety of dental conditions and realize orthodontic archwire curve personalized design.

(4) The object of the position adjustment is the straight section of the bracket in the orthodontic archwire curve. The object of the special function arch curve insertion is the transitional section. The reference points of the mathematical model are two end points of the straight section after adding the compensation value, and the local coordinate system is established.

First, the orthodontics coordinate system O-XYZ is established according to the maxillary data of a patient provided by the orthodontist. The local coordinate system $O_{1}$-UVW is established with the original coordinate O of the global coordinate system as the coordinate origin. The coordinate axis of local coordinate system coincides with the coordinate axis of the global coordinate system, as is shown in Fig. 6. The location of the dental arch target insertion point is obtained through the endpoint $P_2, P_3$ of any concatenated segment on the left and right sides. Finally, the local coordinate system $O_{1}$-UVW coordinate is transformed to the target position. Then the digital expression of the second sequence of special function arc curve is realized. In the Fig. 6. $P_1(x_1, y_1, z_1), P_2(x_2, y_2, z_2), P_3(x_3, y_3, z_3), P_4(x_4, y_4, z_4)$ are the coordinates of a given bracket points.
Fig. 6 The relative position of local and general coordinate

As is shown in Fig. 6, the local coordinate system $O_1$-UVW moves to the target position under the global coordinate $O$-XYZ after three coordinate transformations. The coordinate system $O_1$-UVW first passes the translation by rotating the $\alpha$-angle to the coordinate system $O_1'$-U'V'W' around $O_1W$ axis, the transformation matrix is $R_1$. And the coordinate system $O_1'$-U'V'W' is transformed to coordinate system $O_1''$-U''V''W'' through the translation, the transformation matrix is $R_2$. Coordinate system $O_1''$-U''V''W'' rotated $\beta$ angle around its $O_1''V''$ to the target position $O_1'''$-U'''V'''W''', and the transformation matrix is $R_3$. Assuming that the model equation matrix is $C$ in the local coordinate system of the special arch curve, and the matrix equation of the target position is $D$ in the global coordinate system,

$$D = R_3 \times (C \times R_2) \times R_1 \tag{4}$$

Where,

$$R_1 = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 & 0 \\ \sin \alpha & \cos \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad R_2 = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad R_3 = \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\cos \alpha = \frac{x_1 - x_2}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}, \quad \cos \beta = \frac{x_1 - x_2}{\sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2}},$$

$$x = \frac{x_1 + x_2}{2}, \quad y = \frac{y_1 + y_2}{2}, \quad z = \frac{z_1 + z_2}{2},$$

$$\sin \alpha = \frac{y_1 - y_2}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}, \quad \sin \beta = \frac{z_1 - z_2}{\sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2}}.$$

(5) The position adjustment of the straight section of the brackets refers to the position adjustment of the straight section of the brackets in the plane of the first sequence of the orthodontic archwire. The adjustment is carried out by orthodontic doctor. And the adjustment is relating to the change of the position of the bracket on the teeth and the shape of the orthodontic archwire curve. The position adjustment of the straight section of the bracket is adjusted mainly by two movements, which are the parallel movement of the straight section in the first sequence plane of the orthodontic archwire and the rotation of the two end points of the straight section of the bracket.

The bracket straight section’s position adjustment in the first sequence of the orthodontic archwire is realized through the adjustment of the translation distance, rotation angle and rotation mode. And the straight section coordinates are obtained through the position adjustment in the global coordinates of O-XYZ. In the local coordinate system $O_1''$-U''V''W'' of the straight section, the mathematical model of the straight section of the translation and the rotation around $Q_2$ is $M$. The mathematical model of the straight section of the translation and the rotation around $Q_1$ is $M'$, as is shown in Eq. (5).

$$M = \begin{bmatrix} 1 - \cos \omega & 0 & l \\ h + \sin \omega & h & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad M' = \begin{bmatrix} 0 & 0 & 0 \\ l \cdot \cos \omega & h & h + l \cdot \cos \omega \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$M$ and $M'$ represent the coordinate points equation of the straight section in the local coordinate system. $h$ represents the parallel movement distance of the straight section. $w$ represents the rotation angle. $l$ represents the $Q_1Q_2$ die length. The position adjustment of the straight section is achieved by changing the coordinates of the end points of the straight sections. Therefore, during the setting
of the transitional section, the end points of the transitional sections are adjusted by the end point coordinates which are used as reference points.

(6) The expressing method of parameterized special function arch curve is based on the global coordinate system O-XYZ, which is provided by orthodontist physician. The local coordinate system O1-UVW is established by the two end points of the transitional section. The coordinate matrix D of the special function arch curve under the coordinate system O-XYZ is obtained by the coordinate transformation of the Eq. (4) by using the coordinate matrix C, which is parameterized under the local coordinate system O1-UVW. In the local coordinate system O1-UVW, considering method of manual orthodontics archwire bending, the special function arch curve is regarded as a number of straight section, arc segment and spiral arrangement. The expressions are G, H, K. The expression of the special function is \( F = F \{ G_1, G_2, H_1, K_1, \ldots \} \). The expression is transformed into the coordinate matrix C, and the coordinates of the feature points are stored in the matrix in sequence, as is shown in Fig. 7.

![Fig. 7 Parameterized expression of special function arch curve](image)

Therefore, the position of the special function arch curve is determined by the parameterized value in the coordinate matrix and the coordinates of the two end points of the transitional section. The relative position of the special function arch curve between the two bracket segments is determined by the special function arch curve parameterized expression. In the process of interactive adjustment, the adjustment of the spatial position of the special function arch curve is to change the spatial coordinates of the two reference points by the compensation value setting and the position adjustment of the bracket straight section. The spatial coordinates of two reference points are the spatial coordinates of two end points on transitional sections. \( i (i = 0, \ldots, 12) \) is the position inserting the special function arch curve which means that the position \( i \) corresponds to the \( i \)-th transitional section according to the tooth order of the patient data. The type \( j \) of the special function arch curve \( j (j=0, 1, \ldots) \) is inserted. The default state \( j=0 \) which means the insertion of the transition is based on the Bezier curve, that is, \( D_0 = P(t) \) represents a special function of the type. The coordinate matrix is \( D_j \). For example, let \( j=1 \) represents a large vertical curve, \( j=2 \) for T-shaped curve. Therefore, \( D_j \ (j=1, 2, \ldots) \) represents the mathematical model database of the special function curve. Inserting a special function arch curve represents that, in the position of the \( i \)-th transitional section, the expression of the \( i \)-th transitional section \( P_i(t) \) is replaced by the coordinate matrix \( D_j \) of the \( j \)-th special function arch curve.

### 3.2 Method for the interactive adjustment of orthodontic archwire curve

Orthodontic archwire curve adjustment includes six parts: selecting the patient data, setting compensation value, setting the transitional section, selecting the archwire material, inserting the special function arch curve and adjusting the position of the straight section. In the process of interactive adjustment of personalized orthodontic archwire curves, each part is interrelated with each other. Therefore, the adjustment of the straight section of the brackets is taken into account. Secondly, the end points of the adjusted straight sections of the brackets are the reference points. The adjustment of the transitional section and the special function arch curve is considered on these basics.

The two end points of the transitional sections are the end points of the adjacent two straight sections after the compensation value being added. In the process of interactive adjustment, the compensation value being set and the bracket position being adjusted can change the two ends of the transitional section. But the local coordinate system of the special function arch curve is established by regarding the end points of the transitional section as the reference point. That is, the specific position of the special function arch curve is changed according to the change of the position of the straight section and the change of the compensation value. And selecting position means to select the position between two adjacent teeth then insert a special function arch curve into the position. A special function arch curve can be selected at the same time at multiple locations. And the type of special function curve can be selected to be inserted in the special function arch curve database. Flow chart of interactive adjustment is shown in Fig. 8.

Steps of interactive adjustment:
1) Import the patient data, this is orthodontic archwire forming datum data. The order of the straight sections expressed by FDI is 18, ... , 11, 21, ... 28; (i = 0, 1, ..., 13). According to the order of the teeth, (x2i, y2i, z2i) and (x2i+1, y2i+1, z2i+1) are the i-th teeth' coordinates.

2) Set all the meiso-middle compensation value matrix A = (a0, ... , ai, ... , a13) and the distal-middle compensation value matrix B = (b0, ..., bi, ..., b13). The compensation value is expressed by the orthodontic doctors' familiar expression. The middle parts of the left and right central incisors are regarded as the midline position. The side of the tooth near the middle line is the meiso-middle side. The far side of the tooth away from the middle line is the distal-middle side.

3) The spatial point coordinates [(x2i, y2i, z2i), (x2i+1, y2i+1, z2i+1)] can be obtained through the Eq. (1) when i = 0, 1, ..., 13, that is, the point coordinate matrix T0 can be obtained. T0 includes all the teeth on the jaw corresponding to the straight section of the bracket after compensation value is added, and T = T0.

4) Set the proportional parameter matrix E = (e0, ..., ei, ..., e12) for all transitional sections, F = (f0, ..., fi, ..., f12). Where i = (0, ..., 12) represents the i-th transitional section according to the tooth order of the patient.

5) The two control points N1, N2 coordinates of transitional section can be calculated through the transitional section ratio parameter E, F. According to the tooth position order, if the two adjacent bracket straight section coordinates of the k-th transitional section are [(x2k, y2k, z2k), (x2k+1, y2k+1, z2k+1)], [(x2k+2, y2k+2, z2k+2), (x2k+3, y2k+3, z2k+3)](k = 0, 1, ..., 12), (Xk, Yk) can be obtained through the linear equation under the XY plane projection. (Xk, Yk, Zk) and (Xk, Yk, Zk+i) are obtained by plugging (Xk, Yk) into the spatial straight section general equation. So the four control points of the k-th transitional section are shown in Eq. (3). Plug the four control points of the k-th transitional section into the expression of Bezier curve. As is shown in Eq. (2). The expression of the k-th transitional section is found. When the k = 0, ..., 12, Nk(t) is the expression of all transitional sections Nk(t). The coordinate matrix of the orthodontic archwire curve is
are imported. The local coordinate is the straight
2
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Jiang, Ma, Zuo, Zhang and Liu,
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\[
W = \begin{bmatrix}
X_0 & X_1 & X_{2k} & X_{2k+1} \\
Y_0 & Y_1 & Y_{2k} & Y_{2k+1} \\
Z_0 & Z_1 & Z_{2k} & Z_{2k+1}
\end{bmatrix}
\]

6) Determine whether import the special function arch curve or not. If so, select position \( k \) (\( k = 0, 1, ..., 12 \)), and select the special function arch curve type \( j \) (\( j = 1, 2, ... \)). That is, replace \( N_i(t) \) with \( D_j \) to get the coordinate matrix \( W \) of new orthodontic archwire curve. After that, jump to the next step. If not, jump to the next step.

7) According to the coordinate matrix \( W \) of the orthorhombic archwire curve, the orthogonal curve is generated by connecting the coordinates one by one in sequence, and the curve is displayed in the display window.

8) Determine whether do the position adjustment or not. If so, \( (i = 0, 1, ..., 13) \), indicating the straight section after the addition of the compensation value on the \( i \)-th tooth. Its coordinate is \([X_{2i}, Y_{2i}, Z_{2i}], (X_{2i+1}, Y_{2i+1}, Z_{2i+1})]\). Its length is \( l \). The rotation mode \( m \) (\( m = 0, 1 \)) is selected. \( m = 0 \) means the rotation around mesio-middle point of the straight section. \( m = 1 \) means the rotation around distal-middle point of the straight section. The translation distance \( h \) and rotation angle \( \theta \) are imported. The local coordinate system \( O_1 \) is established through the coordinate \([X_{2i}, Y_{2i}, Z_{2i}], (X_{2i+1}, Y_{2i+1}, Z_{2i+1})]\). In the local coordinate system, \( PF_i \) is the straight section coordinates after the position adjustment. Plug \( PF_i \) into the equation (4). \( PS_i = R_e \times (PF_i \times R_j) \) is the straight section coordinates matrix after transforming to the global coordinate system \( O_1 \). When \( m = 0, i = (0, ..., 6) \) or \( m = 1, i = (7, ..., 13) \), the step (8) should be used. When the \( m = 1, i = (0, ..., 6) \) or \( m = 0, i = (7, ..., 13) \), the step (9) should be used. The step (8) and step (9) are used to calculate \( PF_i \), the straight section coordinate on \( i \)-th tooth after the adjustment. Then jump to the next step. If not, skip to step 11.

9) \( B_i \) is the straight section coordinates after the adjustment. And then \( B_i \) is replaced by the coordinates before the position adjustment \([X_{2i}, Y_{2i}, Z_{2i}], (X_{2i+1}, Y_{2i+1}, Z_{2i+1})]\) to generate a new spatial point coordinate matrix \( T' \). Let \( T = T' \). Then jump to step 4.

10) Determine whether to save the position adjustment of \( i \)-th straight section. If so, then \( T = T \). If not, then \( T = T'' \); jump to step 4.

11) Determine whether to cancel all the position adjustments to restore the default. If so, then \( T = T_0 \). And jump to step 4. If not, then jump to the next step.

12) Save \( W \) the coordinate matrix of the generated orthodontic archwire curve.

13) End of program.

4. Discussion

4.1 Experiment for digital expression and interactive adjustment

Based on the above mathematical models and methods, the LabVIEW software platform is used to realize the parameterized expression and interactive adjustment method of orthodontic archwire curve. The operation interface is shown in Fig. 9. In the figure, the FDI tooth representation of international standard is used in the node control parameter. Each straight section is expressed by using the corresponding teeth’ FDI tooth representation. And each transitional section is expressed by using the two adjacent tooth’ FDI tooth representation.

In order to make the experiment universal, the patients’ data coordinates which are used to stick brackets to maxillary teeth model are collected. That is the 28 reference points. The initial setting of all straight section compensation is 0. And the initial setting of the transitional section proportional parameter is 0. As is shown in figure, that orthodontic arc curve is composed of straight sections which are generated through the connection of the 28 points in turn. The solid line represents the straight sections, and the dotted line represents the transitional sections. A series of adjustments are carried out on orthodontic archwire bending curve. The results are shown in Fig. 10.

Fig. 10a is the initial shape of orthodontic archwire curve. Fig. 10b is the orthodontic archwire curve after setting compensation value. Fig. 10c is the orthodontic archwire curve after the proportional parameter of the transitional section being set. Fig. 10d shows the orthodontic archwire curve in Fig. 10c after the bracket position adjustment in the tooth position 26/11/15/16. Fig. 10e is the orthodontic archwire curve after the insertion of the large vertical arch curve, the lumbar curvature and the tear-shaped curve. Fig. 10f is the orthodontic archwire curve after the insertion of the large vertical curve, \( \Omega \) curve and T-shaped orthodontic archwire curve. Fig. 11 shows an orthodontic archwire with a
tear-shaped arch curve and an arch curve of first sequence for clinical application. By observing and comparing, it can be found that the orthodontic archwire obtained by interactive adjustment is basically the same as the actual orthodontic archwire curve.

Fig. 9 Operating interface of personalized orthodontic archwire

Fig.10 Adjustment results of orthodontic archwire curve

Fig.11 Clinical orthodontic archwire curve

4.2 Experiment for orthodontic archwire bending
In this experiment, the robotic system was calibrated to reduce the experimental error. The robotic orthodontic archwire bending system is shown in Fig. 12. The control software is based on Labview software and mainly includes two modules, upper and lower jaw parameter setting module, orthodontic arch bending control module. The upper and lower jaw parameter setting module is mainly used to read the information of the arch curve, insert special arch curve, adjust the angle and position of the curve line. Orthodontic archwire bending control module is mainly used to control
the individual movements of the robot joints, carry out robotic archwire bending program, interrupt and mediate the operation of the robot. The core of the control unit is a PMAC card. In this system, the pulse signal is amplified by the stepping motor driver to control the coordinated movement of the joints of the robot.

Fig. 12. Robotic orthodontic archwire bending system

The structure diagram of the robot body is as shown in Fig. 13, the movement of the X direction is realized by the ball screw moving platform with effective stroke of 200mm and 10mm guide. The freedoms of Y and Z directions are used to realize the position adjustment between the archwire bending mechanism and the orthodontic archwire. Two ball screw moving platforms with effective stroke of 100mm and 10mm guide are used in this part. The archwire rotating mechanism is connected with the X ball screw moving platform through the L-shape connecting board. The archwire rotating mechanism is mainly composed of a 42 type step motor and a three-claw chuck. The archwire bending mechanism is composed of the 42 type step motor with a planetary gear reducer, a three-claw chuck and a bending gripper. The body of orthodontic archwire bending robot is shown in Fig. 14.

Fig. 13. Structure of orthodontic archwire bending robot

Fig. 14. Body of orthodontic archwire bending robot

The 0.4064mm×0.4064mm stainless steel archwires were used in this experiment. The bending experiment of stainless steel orthodontic archwire was conducted by the robotic orthodontic archwire bending system with the
adjustment of this interactive adjustment method. The 0.4064mm×0.4064mm stainless steel orthodontic archwires were used in this experiment. Respectively, \( l_1 \) and \( w_1 \) are the height and width of the canine teeth offset, \( l_2 \) and \( w_2 \) are the height and width of the molar offset, \( l_3 \) and \( w_3 \) are the height and width of the dental arch. And \( l_1, l_2, l_3, w_1, w_2, w_3 \) are the important parameters usually used to design the orthodontic archwire. And they are also the standards for measuring the bending accuracy of the archwire in this experimental. The ideal dental parameters of the patient are shown in Fig. 15. The ideal parameters are used to compare with the experimental results in the next part.

The experimental 14 maxillary teeth data information of the patient is provided by the Peking University School of Stomatology, as shown in Table 1. In the experimental process, the open vertical loop was inserted to the archwire curve. The model of the archwire curve was established through the proposed digital expression method. When an archwire needed to be bent, the bending platform needed to change. After a first sequence curve bending, the archwire should be fed by the X ball screw moving platform to realize the bending of a second sequence curve. And the step motor of the archwire rotating mechanism rotates in clockwise or anti-clockwise direction. The rotation direction is depends on the shape of the archwire curve. The archwire rotates with the rotation of the step motor. At this time, the bending gripper is driven by the rotation of the step motor of the archwire bending mechanism and rotates in clockwise. After that, the step motor of the archwire bending mechanism rotates in the negative direction to reset the position of the bending gripper. The bending of the second sequence curve can be realized by these movements. And an archwire can be bent by the combination of these movements of the orthodontic archwire bending robot (Jiang et al., 2018). The experimental bending process is shown in Fig. 16.

Table 1 Experimental maxillary teeth data information

| No. | (X,Y) [mm]   | No. | (X,Y) [mm]   | No. | (X,Y) [mm]   |
|-----|--------------|-----|--------------|-----|--------------|
| 1   | (8.83, 15.40)| 11  | (25.20, 59.80)| 21  | (63.60, 46.70)|
| 2   | (9.47, 19.30)| 12  | (27.80, 61.40)| 22  | (64.80, 43.40)|
| 3   | (10.3, 24.50)| 13  | (33.40, 64.50)| 23  | (66.90, 37.40)|
| 4   | (11.20, 29.30)| 14  | (37.60, 65.20)| 24  | (67.70, 33.90)|
| 5   | (12.20, 35.20)| 15  | (43.00, 65.30)| 25  | (68.50, 28.60)|
| 6   | (13.50, 38.90)| 16  | (46.70, 64.20)| 26  | (69.00, 24.90)|
| 7   | (14.90, 44.20)| 17  | (51.70, 61.50)| 27  | (69.60, 19.60)|
| 8   | (16.60, 48.20)| 18  | (54.30, 60.00)| 28  | (69.80, 15.40)|
| 9   | (19.10, 52.30)| 19  | (58.90, 55.20)|   |
| 10  | (21.60, 55.70)| 20  | (60.80, 52.50)|   |

4.3 Experimental result for orthodontic archwire bending

The archwire bending by using the digital expression and interactive adjustment method is shown in Fig. 17. The ideal dimension parameter, actual parameters and the error rate are shown in Table 2.
Fig. 16 Experimental process

Fig. 17 Orthodontic archwire curve bent in the experimental process

Table 2 Archwire comparison between experimental and theoretical values

| Parameter   | \(w_1\)[mm] | \(w_2\)[mm] | \(w_3\)[mm] | \(l_1\)[mm] | \(l_2\)[mm] | \(l_3\)[mm] | \(h\)[mm] | \(d\)[mm] |
|-------------|--------------|--------------|--------------|------------|------------|------------|---------|---------|
| Ideal value | 37.3         | 53.5         | 60.1         | 9.9        | 27.2       | 45.9       | 7.0     | 3.0     |
| Experimental value | 39.4         | 54.3         | 61.2         | 10.2       | 26.9       | 45.4       | 6.9     | 3.2     |
| Difference value | 2.1          | 0.4          | 1.1          | 0.3        | -0.3       | -0.5       | 0.1     | 0.2     |
| Error rate  | 5.6%         | 1.5%         | 1.8%         | 3.0%       | 1.1%       | 1.1%       | 1.4%    | 6.7%    |

Through the comparison of the ideal archwire curve and the actual archwire curve, it can be found that the shape of the ideal archwire curve is basically the same as the actual orthodontic archwire curve. The error rate ranged between 1.1% and 6.7%. The bending accuracy can meet the demand of the orthodontic which proves that the digital expression and interactive adjustment method of personalized orthodontic archwire for robotic bending is effective.

5. Conclusion

Based on the reference points on the brackets, the straight sections and the transitional sections of the orthodontic archwire curve are established. Considering the process of manual orthodontic archwire bending, the mathematical model of the special function arch curve is established based on the discrete and combined method. According to the characteristics of the teeth movement, the method of adjusting the bracket straight section position and the combination of the special function arch curve and the first sequence arch curve are analyzed. Based on these methods, an orthodontic archwire intermodulation method is proposed to realize the personalized expression of orthodontic archwire. Based on the LABVIEW software platform, the orthodontic archwire interactive adjustment software was developed. The reference point coordinates of the adhesive brackets on the maxillary tooth model were collected as experimental data, and the interactive adjustment experiment of orthodontic archwire curve was carried out. The experimental results show that the position of each straight section can adjust by this method to change the arch shape of the orthodontic archwire. The error rate of the bent archwire ranged between 1.1% and 6.7% which proves the digital expression and interactive adjustment method of personalized orthodontic archwire for robotic bending is feasible and effective.

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