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TOOTH ALIGNMENT OF THE DENTAL CAST USING 3D THIN PLATE SPLINE

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ABSTRACT
This article has described the process for tooth alignment using 3D thin plate spline. First step is to simulate the individual tooth and its landmarks and fit it into the dental cast by geometric transformation of individual tooth. Next step is to align the simulated teeth into proper arch form. After that, record pairs the landmarks of simulated teeth before and after tooth alignment. The final step is to create the new dental cast (warping dental cast) by applying 3D thin plate spline technique through pairs of landmarks on simulated teeth as inputs. The results of the tooth alignment and the comparison with the dental cast before tooth alignment have shown that the teeth aligned along the curve while the gum was slightly deformed to show the smoothness of transformation on teeth and gum.

KEY WORDS
Visualisation, Simulation, Thin plate spline, Teeth Alignment

1. Introduction

The orthodontics analyses have relied upon dental casts made from plaster of Paris with silicone mold for a long time. The states-of-the-art technologies have allowed orthodontic diagnostic, analyses and treatments planning in 3D images of dental casts through commercial software on personal computers. OrthoCAD of Cadent Inc. [1], 3Dxer of Dimemnex Digital Lab [2] and e-model from Geodigm Corp. [3] and Application Visualization System Express of Advanced Visual System Inc.[4] are a few examples of software for 3D orthodontic planning and analyses.

However, existing commercial software for 3D orthodontic analyses has a limitation of displaying only crown section of the dental cast without taking anatomy information of dental roots into account. [5] Even though there are some researches for the complete 3D model of human jaw including dental crowns and roots [6], it requires rigid registration and then matching on both dental crowns and roots with the 3D Freeform Deformation (FFD) dental models which is a time-consuming process.

Macchi [7] has developed the technique for 3D superimposition of anatomic teeth and cast model. However, the software mentioned in Macchi's paper is not easy to use and also required the significant user skill. Furthermore, we have found the similar problem when we tried to perform image registration between CT images and model image due to the sheer amount of 3D data which complicate the difficulty to segment the 3D CT model.

2. Method

2.1 Registration between Dental Cast and Simulated Teeth

This section, first the simulated teeth were created using 3D Studio Max [8]. The enamel-crowns template shown in Fig. 1(A) was scanned and segmented to be a template of 3D crowns. The dental roots were designed and attached to the crowns as shown in Fig. 1(B). The result of the simulated 3D teeth model can be shown as in fig. 1 (C), which shows the side and top views respectively. Also the teeth landmarks of each tooth have been located on the surface of the simulated teeth as can be seen in fig 1(C) as well. Next step is to locate the occlusal landmarks on the top of each tooth or at some selected teeth and apply cubic spline technique [9] to fit the landmark as the trace line positions in 3D. To locate the occusal landmarks, user needs to click on the 3D object to locate the landmarks. Normally the software recognizes the landmarks located by user on screen as screen coordinates. Therefore, it is needed to call gluUnproject function from openGL library to convert screen coordinates into to 3D model coordinates. To apply the 2D-to-3D coordinate conversion on mouse coordinates, several variables has to pass into the functions such as function for viewport origin and extent, modelview Matrix, projection matrix and the windows screen coordinate which can be obtained using some opengl functions. [10]

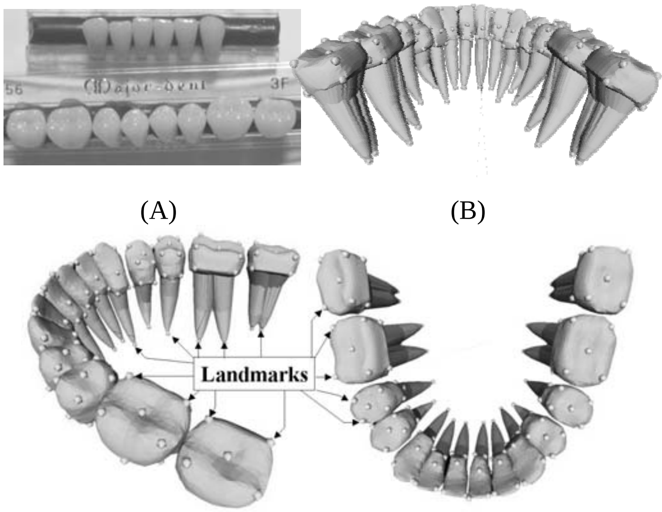


Fig. 1: Simulated Teeth with roots using 3D Studio Max.

A) The enamel-crown template used in the dental lab.
B) 3D Crowns created from the template.
C) Side and top view of Simulated Teeth with roots.

Once locating occlusal landmarks, the cubic spline algorithm will be executed to generate trace line and the landmarks. The cubic spline consists of sections of polynomial curves connected at these landmarks. The polynomials of a given spline all have the same degree in X, Y and Z and fit the control points as 3D line.

The spline is obtained by calculating the second derivatives of the interpolating function at the tabulated points based on the formulation given in “Numerical Recipes in C”. [11] The result of fitting the 3D line with cubic-spline interpolation can be seen as in Fig. 2.

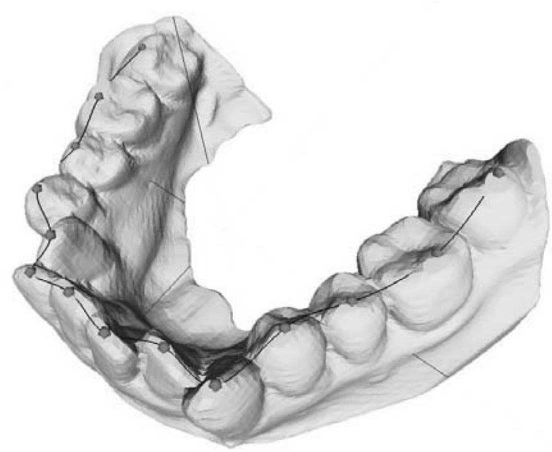


Fig. 2: Cubic spline fitting line on the occlusal landmarks

The occlusal line was applied to calculate the starting position of the 3D simulated teeth. Then, each tooth was translated, rotated and scaled in to the right position to fit the dental cast by using the function provided in our software. Once every tooth has been moved to match the cast, then the user can saved it and open it later on without registration every time running.

Translation expression can be seen in (1).

$$P_T^{'} = R_T + P = \begin{bmatrix} t_{x1}+x_1 & t_{y1}+y_1 & t_{z1}+y_1 \\ ... & ... & .. \\ t_{xN}+x_N & t_{yN}+y_N & t_{zN}+z_N \end{bmatrix} \quad (1)$$

The rotation about x-axis, y-axis and z-axis can be seen in (2A), (2B) and (2C) according to Euler angles. [12]

$$P_{RX}^{'} = R_X P, R_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_x) & -\sin(\theta_x) \\ 0 & \sin(\theta_x) & \cos(\theta_x) \end{bmatrix} \quad (2A)$$

$$P_{RY}^{'} = R_Y P, R_Y = \begin{bmatrix} \cos(\theta_y) & 0 & \sin(\theta_y) \\ 0 & 1 & 0 \\ -\sin(\theta_y) & 0 & \cos(\theta_y) \end{bmatrix} \quad (2B)$$

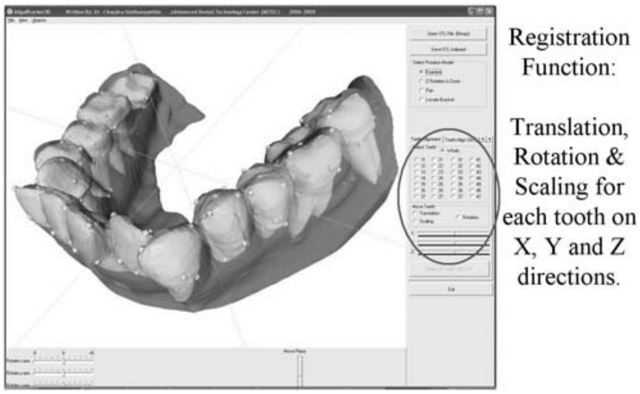
$$P_{RZ}^{'} = R_Z P, R_Z = \begin{bmatrix} \cos(\theta_z) & -\sin(\theta_z) & 0 \\ \sin(\theta_z) & \cos(\theta_z) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2C)$$

The scaling technique can be expressed as (3) where S is the scaling value.

$$P_S^{'} = SP = \begin{bmatrix} S*x_1 & S*y_1 & S*z_{z1} \\ ... & ... & ... \\ S*x_N & S*y_N & S*z_N \end{bmatrix} \quad (3)$$

The registration tool that has been developed for this project let the user be able to move, rotate and scale the teeth template to match the dental cast as shown in Fig 3. Fig. 3(A) shows the result before the registration while Fig. 3(B) shows the result for moving, rotating and scaling individual teeth on the teeth template. Fig 3(C) shows the final result of image registration of teeth template on dental cast while program in Fig 3(D) shows the cast with 60 % translucent to enable user to see the roots inside the cast along with the mechanic for moving the individual tooth.

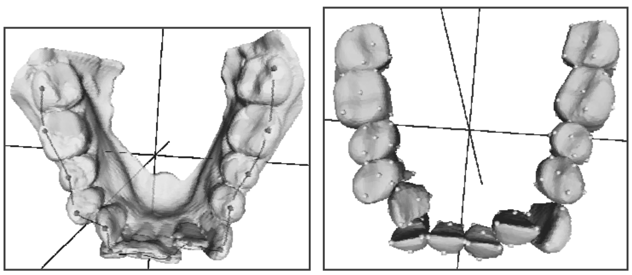
(A) (B) (C)



(D)

Fig 3: Simulated teeth registering on the dental cast.

2.2 Simulated Teeth Alignment

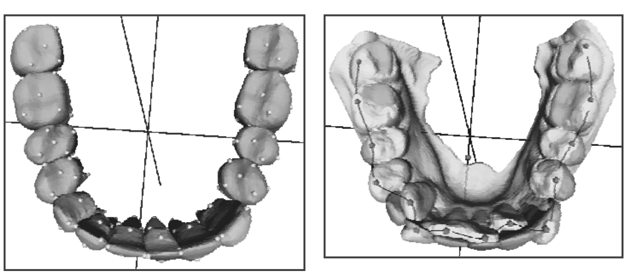


(A) (B)

Fig. 4: Initializing the teeth alignment.

In the experiment of tooth alignment without causing dental roots protruding out of the gum in the dental cast, the first step is to setup the initial position for simulating teeth alignment. Researchers have defined the occlusal landmarks in red for each tooth in the dental cast in to draw the trace line and then superimpose the teeth template on the dental cast as shown in Fig. 4(A) to set the initial teeth positions before performing teeth alignment as shown in Fig. 4(B)

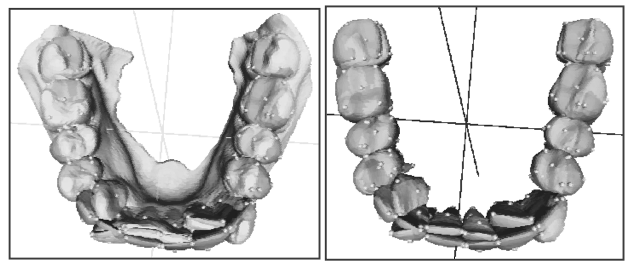
After the initialization, the next step is to set the final positions for the teeth alignment. This can be done by applying a teeth template with geometric transformation into the proper alignment as shown in Fig. 5(A). Comparison of the proper simulated teeth alignment and the dental cast can be seen as in Fig. 5(B).



(A) (B)

Fig 5: Simulating the final positions for teeth template.

After simulating the final positions for teeth template, the next step is to compare the landmarks of the initial simulated teeth with corresponding landmarks on the aligned teeth template as shown in Fig. 6. Fig. 6(A) shows the result of paring landmarks with the dental cast while Fig 6(B) shows the results of paring without dental cast.



(A) (B)

Fig. 6: The results of paring landmarks.

2.3 Dental Cast Warping based on 3D Thin Plate Spline

To generate the new dental cast, it becomes necessary to apply algorithms to create the new model from the teeth movement data. One of the algorithms for this task is Thin Plate Spline (TPS).

Thin plate spline (TPS) [13] is the technique for estimating the random data from 2 paring sets of data to construct spline map from the affine factor for linear distortion and weighting factor for nonlinear distortion for image registration. The first step of TPS is to solve (4) to calculate both affine factor A and weighting factor W.

$$\begin{bmatrix} K & \hat{P} \\ \hat{P}^T & O(4,4) \end{bmatrix} \begin{bmatrix} W \\ A \end{bmatrix} = \begin{bmatrix} V \\ O(4,3) \end{bmatrix} \quad (4)$$

O(r,w) is zero matrix of 4x4 and 4x3 respectively. $\hat{P}^T$ is a matrix $\hat{P}$ that has rows and columns switched (transposed $\hat{P}$ matrix). $\hat{P}$ is an initial landmark position set matrix before moving with the additional value 1 in every row defined in (5) while K is a matrix $U(r)$ defined as a function of distance between each landmark r for image distortion by 3D Thin Plate Spline process as defined in (6) and (7) respectively, and V is an final landmark position set matrix after moving the landmarks defined in (8) with N is the number of start-stop landmark pairs.

$$\hat{P} = \quad [Ones(1,N),P] = \begin{bmatrix} 1 & x_1 & y_1 & z_1 \\ ... & ... & ... & ... \\ 1 & x_N & y_{N1} & z_N \end{bmatrix} \quad (5)$$

$$K = \begin{bmatrix} 0 & U(r_{12}) & \dots & U_{1(N-1)} & U(r_{1N}) \\ U(r_{21}) & 0 & \dots & U_{2(N-1)} & U(r_{2N}) \\ \dots & \dots & \dots & \dots & \dots \\ U(r_{(N-1)1}) & U(r_{(N-1)2}) & \dots & 0 & U(r_{(N-1)N}) \\ U(r_{N1}) & U(r_{N2}) & \dots & U(r_{N(N-1)}) & 0 \end{bmatrix} \quad (6)$$

$$e.g.: r_{1,2} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (7)$$

$$V = \begin{bmatrix} x_1^{'} & y_1^{'} & z_1^{'} \\ \dots & \dots & \dots \\ x_N^{'} & y_N^{'} & z_N^{'} \end{bmatrix} \quad (8)$$

Fig. 7 shows the result from 3D Thin Plate Spline applied on the skeleton model with 10 pairs of landmarks as demonstrated in [14]. Fig. 7(A) showed the skeletal before applying 3D TPS while Fig. 7(B) shows the final result after 3D thin plate spline.

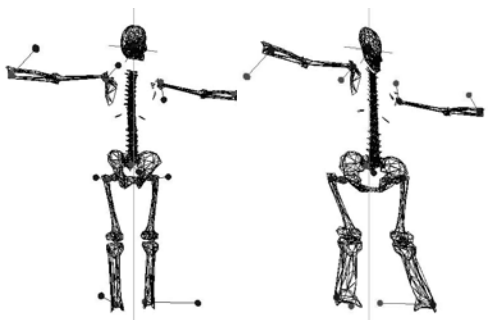
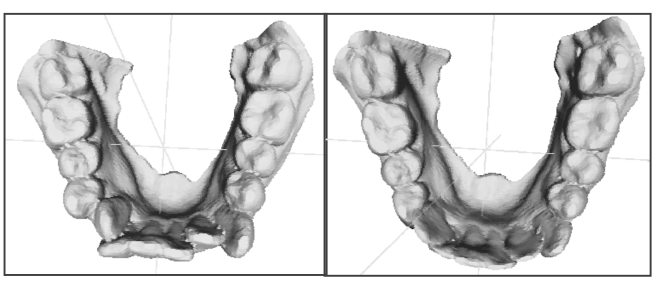


Fig. 7.TPS Application in 3D on the Skeletal Model

3. Results

The experiment results show the dental cast before tooth alignment as Fig. 8(A) while Fig 8(B) shows the final results after performing tooth alignment using 3D Thin Plate Spline technique.



(A) (B)

Fig. 8 Comparing the Teeth Alignment Results

The results showing in Fig. 9 are the superimposition of the final teeth alignment with the initial dental cast in different angles. The result has shown that there is no dental root protruding out of the old and the new dental cast as well.

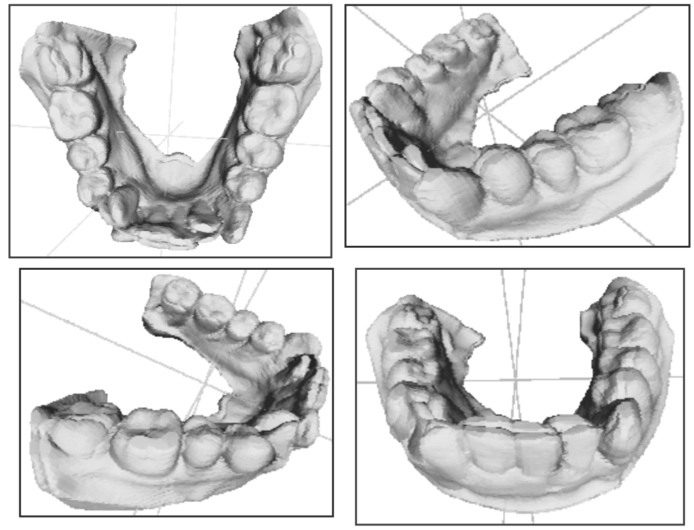


Fig. 9 The superimposition of the results teeth alignment

However, there are some distortions on the individual teeth after performing tooth alignment due to the effect of 3D Thin Plate Spline. The individual teeth are not supposed to be distorted shapes since they are inelastic compared with the gum section.

Further development is to perform segmentation on individual teeth as shown the case of marker-controlled mesh segmentation [15] or automatic segmentation by using range images to detect both dental arch and tooth interstices before segmentation [16]. Next step after segmentation is to applied proper 3D cubic spline interpolation algorithms on the model mesh to fill the missing parts of individual teeth. These algorithms would allow users to perform teeth alignment with minimized shape distortion on each tooth by separating teeth out of the model before performing 3D Thin plate Spline.

4. Conclusion

We have proposed an approach to align teeth on the dental cast for orthodontic planning by applying 3D thin plate spline technique. This method has used a set of teeth with crowns and roots as a template to match with teeth on the dental cast to set the initial positions for landmarks on dental template. After performing teeth alignment to set the final positions for landmarks on dental plate, we perform 3D thin plate spline to create the new model of dental cast. Our approach depends only on the changing positions of landmarks on the template without relying upon CT scan data which are expensive imaging. The application of image registration is to match the dental template with dental cast with the best fit with available upper parts of teeth. The application of 3D thin plate spline is to create the new dental model after orthodontic treatment to apply orthodontists to predict the final results of the treatment in advance.

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