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Development of a Virtual Orthodontic Alignment System using a Haptic Device

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ABSTRACT

This paper presents an efficient and economic virtual teeth setup system. The virtual teeth set-up procedure follows the traditional method of using aligners to assist the dentist in solving orthodontic problems. Unlike the traditional method, our virtual set-up procedure first digitizes a plaster model using a 3D scanner. Next, crown segmentation algorithm is used to separate the virtual model into the teeth and gum. The virtual teeth can be adjusted by a force feedback device. During the chewing motion, the continuous detection algorithm is used to prevent the teeth from intersecting. In addition, in order to avoid defects while the teeth are moving, the morphing algorithm is used to deform the virtual gum during teeth movement. After orthodontic planning is finished in our system, a new orthodontic treatment method, called clear aligner, will be added to our system. First, each step of set-up model can be milled using a 5-axis machine. Then the clear aligner can be manufactured by vacuum forming technology. Finally, a clinical experiment is conducted to validate our virtual teeth set-up system. The contribution of this paper is to propose an innovative procedure designed for orthodontic alignment. It is believed that our system can greatly reduce the cost of orthodontic treatment and facilitate the conduct of orthodontic study.

Keywords: segmentation, gum deformation, collision detection, orthodontics.
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1. INTRODUCTION

Orthodontic treatment is concerned with the treatment of malocclusion. Known more commonly as crowded teeth, cross bite, overbite, under bite, or open bite, malocclusion is a common problem seen in most people at least to some degree. Malocclusion can be attributed to three main causes: heredity, tooth loss, or oral habits. In terms of heredity, the size, shape and structure of our jaw bones and teeth are determined by our genes. If a family has a history of large teeth, it is very likely that new generations will have them as well. These genetic factors may result in large or small teeth in a normal mouth, or normal teeth in a small or a large jaw. Any asymmetry between the teeth and jaws can cause malocclusion and lead to orthodontic problems. Large teeth in a small jaw will crowd each other, while small teeth in a larger jaw will shift out of place, causing spacing problems. Another cause of malocclusion is loss of one or more teeth. When a tooth is lost, nearby teeth tend to shift into the newly available space, moving them out of alignment. The last reason for malocclusion is oral habits. Oral habits that place ongoing or frequent pressure on the teeth may slowly move the teeth out of place. The most common oral habits that cause malocclusion include: thumb-sucking, finger-sucking, pacifier use, and mouth breath. Poor habit may cause malocclusion in young children. However, when a child stops the sucking habit, the teeth will naturally begin to move back to their original positions. Orthodontists believe that oral habits can lead to future orthodontic and facial development problems.

Although malocclusion has a strong impact upon our lives, it is not impossible to treat. Nowadays, braces are the most common orthodontic treatment for malocclusion. The doctor first places gummy plaster in the patient's mouth to get an impression of the teeth and the gum, and plaster model is made of the teeth and gum. After impression, dental technicians separate the plaster model into single tooth dies and determine the final position of the teeth. After that, brackets are placed on the teeth and a wire is pulled through the brackets, which will begin to straighten the teeth. Generally the time for treatment is about one or two years, depending on the complexity of a patient's teeth. However, this type of orthodontic treatment is labor-consuming, and only highly experienced technicians can do it.

Recently, progress has been made in the area of CAD/CAM technology and scanner technology. The technology is used to assist dental treatment in a virtual environment. There are already some virtual dental systems, which are fully based on computer aided design and manufacturing.

In this paper, we propose a virtual teeth setup system which integrates a force feedback device. Section 2 provides a brief survey of related research and developed systems. Section 3 explains the system architecture. Section 4 discusses the virtual teeth separation algorithm and virtual gum deformation approach. In section 5, the collision detection method and mass-spring-damper system are applied to enhance our setup system to be more realistic. Section 6 presents a clinical experiment of our clear aligner treatment. Finally, we present the results and conclusions in section 7.

2. RELATED WORK

With CAD / CAM technology and computer technology advances, the mesh processing engine has been successfully applied to virtual modeling. In this paper, we will briefly describe the literature which is close to our research.

2.1 Mesh Segmentation

Z. Li et al [1] proposed an algorithm which is based on the marching watersheds and marker controlled method. Their algorithm guarantees a closed outline for a segmented region by selecting a point as the seed. The region growing method will be terminated according to the curvature. M. Zhao et al [2] accurately segmented the teeth individually based on the feature of the teeth. Their system utilizes the value of a curvature to identify the characteristics of geographical areas. Finally, the four reference points which define the lingual side and buccal side can be obtained to filter out noise feature lines. In addition, Q. YU et al [3] also used the curvature of the mesh to identify characteristic regions between the crown and the gum. The skeleton extracting method will be applied to attenuate the desired region.

2.2 Mesh Deformation

There have been many studies on the modeling and animation of deformable objects. These methods can be classified into two categories: space-based and surface-based. The former is a vector-field format used to determine the shape of a deformable object, which is divided into three categories: (1) Curves [4]: the deformable object is applied by the curves. (2) Lattices [5]: the model is encompassed by the lattices. The deformation will be accomplished by controlling the shape of the lattice vector. (3) Point [6]: the object is enveloped by a point array. The shape can be modified while the point's location is changed by referencing the weighting values between the object and all the points. Furthermore, volume preservation [7] and self-intersection are also the essential property for mesh deformation. Volume preservation means that the volume of an object can be maintained during deformation, and self-intersection focuses on the avoidance of penetration. Those properties enable a deformation suitable for industrial applications.

The surface-based method is a method which deforms the shape of an object by directly modifying the object's data. A common approach is based on triangular meshes. The method specifies a number of original and target vertices, and uses these data to calculate the vertices which are not specified. J. Parus, and others [9] found the corresponding features between the source and target object. This method can effectively achieve the purpose of deformation. Y. Lipman et al [10] solved the time-consuming problem by using the linear least squares method. They also constrained the surface feature by applying these constraints on mesh vertices.

2.3 Collision Detection

R. Seidel et al [13] proposed an algorithm which could speed up collision detection by using the Convex Hull method. Because the Convex Hull method can envelop an object completely using few points, this method can be efficient only by taking a few points into account. MC Lin et al [14] presented an algorithm which could establish a Voronoi region around an object. A collision can be detected in this offset region. Their method can save a lot of time during collision detection. Abdel-Malek, and D. Blackmore [15] constructed a swept volume, which is the region that an object passes. Their method can find collisions by checking the intersection of swept volumes. However this method needs a lot of time to perform continuous collision detection. A. Kheddar [16] proposed a highly efficient collision detection algorithm by calculating the first contact of two objects. Their method avoids penetration or other collision mistakes. It is also effective for the detection of very thin objects or of high speed objects. F. Schwarzer, and M. Saha [17] mentioned the use of linear motion to define an object's motion. Their method can interpolate those positions from A to B by interpolation. It is more efficient to find an intersection when a collision happens.

3. SYSTEM OVERVIEW

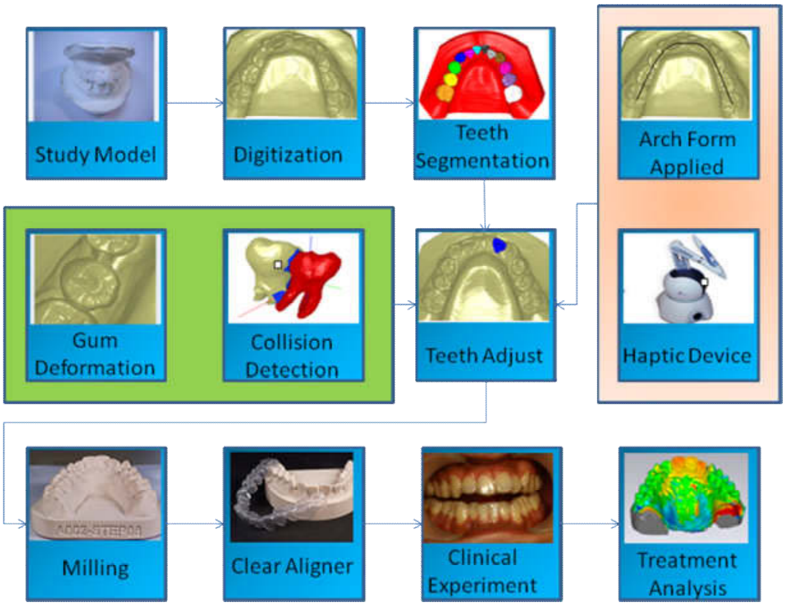

Fig. 1: The flowchart of the system presented in this paper.

In this section, we give a brief description of our virtual teeth setup system. The main flowchart is given in Fig. 1. First, the study model has to be digitized into a virtual object. In order to adjust individual tooth, teeth segmentation is necessary in order to separate the teeth from the gum by detecting mesh characteristics. Gum deformation and collision detection enable the user to adjust the teeth smoothly and naturally. This research also integrates the haptic device to provide an intuitive interaction. The arch form applied is the target that gradually corrects dental movement. After teeth adjustment is finished, each step of the setup model can be milled by a 5-axis milling machine to produce an intermediate model. Then a clear aligner, which will be used to correct the teeth, can be fabricated by using the vacuum forming technology. This paper also provides a clinical test of the clear aligner treatment. Finally, the difference between the before and after treatment can be clearly revealed by the treatment analysis.

4. MESH SEGMENTATION AND GUM DEFORMATION

4.1 Mesh Segmentation

A few of the other virtual setup systems can separate teeth individually with accuracy and efficiency. Most of them build the setup models manually. A dental technician first separates the study model into individual tooth dies. Then, these separated tooth dies are digitized using a 3D scanner. Finally, the virtual teeth can be merged into a complete setup model.

Obviously, the traditional procedure is laborious and time-consuming. This paper proposes an algorithm which can detect the feature region correctly by referencing the mesh curvature. In our system, our goal is to separate the teeth from the gum accurately. The teeth are imbedded into the gum. If gingival grooves can be detected correctly, the teeth could be separated precisely. However, because of the smoothing effect during digitization, some features will be lost during scanning. The results of feature detection would appear as discontinuous regions. In order to overcome this difficulty, our proposed system provides a paint tool that allows the user to repair the non-detected regions. Further, a thinning method is applied to obtain the partition between the teeth and gum correctly. Using such tools, we can ensure that each tooth will be separated by the gingival groove. Finally, the user needs to select a triangle as the seed. The teeth can be separated thoroughly after the region-growing method is executed.

The dental segmentation flowchart is shown in Fig. 2. Each tooth is extracted accurately and efficiently. Fig. 3 shows the result after our dental segmentation algorithm is applied.

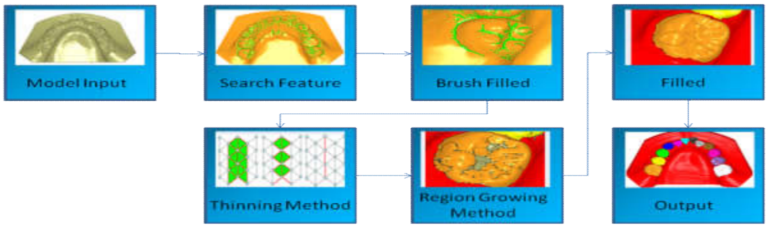

Fig. 2: Flowchart of teeth segmentation.

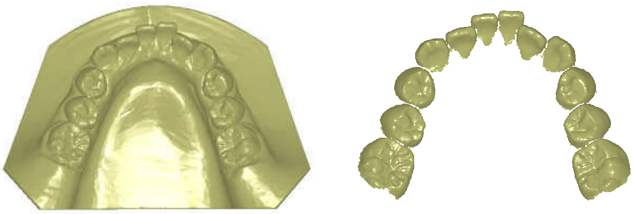

Fig. 3: The result of teeth segmentation.

4.2 Gum Deformation

After teeth segmentation is implemented, the original virtual study model can be separated into the teeth and gum. In a physical sense, the gum should deform naturally while the teeth are being moved in treatment. But in a virtual environment, the teeth and gum will split away if the connection between the teeth and gum is not constructed first. In order to overcome this drawback and present a realistic simulation, this paper utilizes a morphing algorithm to simulate the deformation of gum.

For each tooth, each boundary point of a tooth can be regarded as an anchor point. If we define tooth S to have anchor points $q_i, i = 1,....,n$, after a tooth is adjusted, it is natural that there will be corresponding anchor points $q_i', i = 1,.....,n$ on the same tooth S'. The transformation W will result in:

$$q_i' = W(q_i), i = 1,....., n \tag{1}$$

We can write the transformation equation W as follows:

$$W_t(x) = ((1-t)I + tE)(R_t x + tT), \qquad x \in R^3 \tag{2}$$

where R and T are defined as the rotation and translation matrix, respectively, and E is a warping transformation which is built as the radial basis function (RBF). Fig. 4 describes our gum deformation pipeline. Fig.5 shows the result of gum deformation.

Fig. 4: Flowchart of gum deformation.

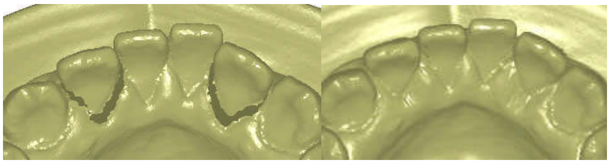

Fig. 5: Left: without gum deformation; Right: with gum deformation.

5. FORCE FEEDBACK SET-UP SYSTEM

A force feedback device is an essential component in interactive simulations. This paper proposes a virtual teeth set-up system that allows the user to simulate the process of orthodontic treatment and predict the treatment result precisely. Using this system, a dentist does not need to use a plaster model for training. The procedure can be repeated again and again. In addition, for efficiency, the force feedback haptic device is integrated into our system. The haptic device allows the user to touch objects in a virtual environment and experience force directly. In our system, the user can manipulate the generic style of the force-feedback device to control the teeth position and rotation. If teeth intersection occurs, the system yields a feedback force to prevent the tool from moving forward.

Nevertheless, in order to operate the haptic device smoothly, the required display rate is over 30 frames per second, and the update rate for haptic interaction must be higher than 1k-Hz to ensure continuous interaction and smooth transitions.

5.1 Collision Detection

In computer graphics, collision detection is a means to test possible interference between two objects. A high efficiency and accurate collision detection is essential and necessary to simulate physical behavior in a virtual environment. In our system, a dentist adjusts the virtual teeth by directly using a haptic device. The teeth must not intersect each other during setup. In order to avoid this intersection problem, the collision detection algorithm must be used to find any intersection between the teeth, and to calculate the feedback force according to the depth of the intersection. Broadly, collision detection can be categorized into two types:

(1) Discrete collision: Two objects can be checked for intersection at a fixed time interval. However, this method cannot determine whether two objects will collide during motion. Fig. 6 (Left) shows the result of discrete collision.

(2) Continuous collision: This method will determine the sweep path of two objects by interpolation. In this way, collision detection can be implemented in each step. The objects will cease any minute when collision happens. Fig. 6 (Right) shows the result of continuous collision.

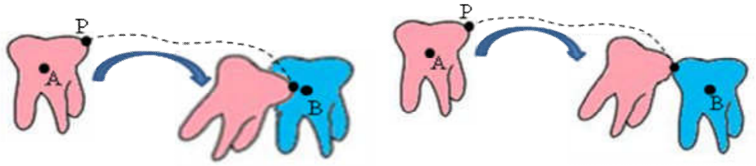

Fig. 6: Collision detection of teeth. Left: discrete; Right: continuous.

Since we want to continuously detect any collision while the teeth are moving, we have to determine the trajectory of each tooth first. Teeth roots are normally constrained in the alveolar; the dentist cannot move specific tooth arbitrarily. For example, if a patient has a maxillary protrusion problem, the incisor can't be adjusted in a backward direction immediately. The dentist has to move the canine teeth first in order to provide enough space for the incisor. Otherwise, the teeth will huddle together during orthodontic treatment. Here, we put the teeth from this step to the next and interpolate the temporary location at the same time. In this paper, a linear interpolation method [21] is used for the purpose of efficiency and real-time display.

Once the initial and final positions of the teeth are determined, the rigid motion ***M*** which includes translation ***T*** and rotation ***R***, can be calculated. The rigid motion ***M*** can be represented as follows:

$$M(t) = \begin{pmatrix} R(t) & T(t) \\ (0,0,0) & 1 \end{pmatrix} \tag{3}$$

The translation ***T*** and rotation ***R*** can be defined separately as:

$$T(t) = T_0 + tv \tag{4}$$

where v represents the velocity of translation.

$$R(t) = \cos(wt)\cdot A + \sin(wt)\cdot B + C \tag{5}$$

where A, B and C are all 3×3 matrix coefficients which can be expressed as following:

$$\begin{aligned} A &= R_0 - u\,u^T R_0 \\ B &= u^* R_0 \\ C &= u\,u^T R_0 \end{aligned} \tag{6}$$

(u, w) r represent the angular velocity of tooth and u* is the skew symmetric matrix when $u = (u^x, u^y, u^z)^T$

$$u^* = \begin{pmatrix} 0 & -u^z & u^y \\ u^z & 0 & -u^x \\ -u^y & u^x & 0 \end{pmatrix} \tag{7}$$

Finally, the method mentioned above can associate the convex-hull tree and bounding volume hierarchies [19] during calculation if the distance between two teeth is less than the threshold. If it is, the two teeth can be taken to have collided. Their motion would be interrupted at the position where the collision took place. Fig. 7 shows the result of collision detection. The left shows the result of discrete collision detection; the right shows the position without teeth collision.

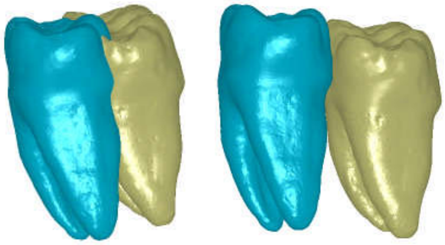

Fig. 7: Left: collision; Right: without collision.

5.2 Force Calculation

The force feedback device allows the user to interact intuitively in a virtual environment. Correct force calculation is still an open issue since it is not easy to calibrate the property of a physical object for use in virtual computation and simulation. Generally, the mass-spring-damper system is the most popular model to simulate force. Fig. 8 shows a mass-spring damper system diagram. If the distance of the spring changes from x_1 to x_2, the force can be calculated by using Equation 8.

$$\vec{F} = k \cdot \Delta\vec{d} - b \cdot v \tag{8}$$

where k is the coefficient of the spring; $\Delta\vec{d}$ is the compressed distance; b represents viscosity; and v is the velocity of the model.

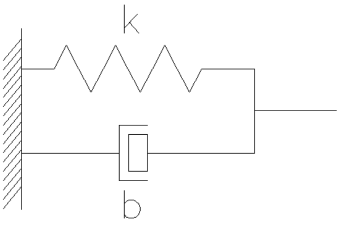

Fig. 8: Mass-spring damper system.

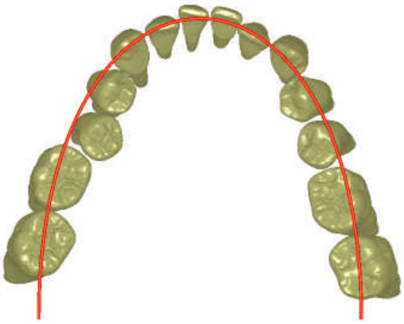

Fig. 9: Arch wire display.

The arch wire is an essential reference when orthodontic alignment is implemented. Fig. 9 shows the relation between the arch wire and the teeth. In our system, we use an arch wire to calculate the attractive force of the teeth. The attractive force will drive the teeth to the desired positions. The details are as follows:

1. Define the centric of each tooth.
2. Calculate the closest point $P_{\min}$ on the arch wire and the shortest distance $d_{\min}$ from $P_{\min}$ to the tooth centroid.
2. The vector n can be obtained between $P_{\min}$ and COM (Center of Mass).
3. The length of the mass-spring damper system can be regarded as $d_{\min}$, and the direction is n.
4. The attractive force can be calculated from Eqn. (8).

6. RESULT AND CLINICAL EXPERIEMNTS

Using our system, a dentist can plan the orthodontic alignment procedure virtually. The collision detection method and the force feedback device help the dentist interact intuitively with the virtual orthodontic system. In order to facilitate the process of producing clear aligners, the virtual gum deform together to keep the model enclosed during teeth movement. Fig. 10 shows each step of the setup model after planning by a dentist. As can be seen, each step of alignment has a slight movement compared to the one next to it .

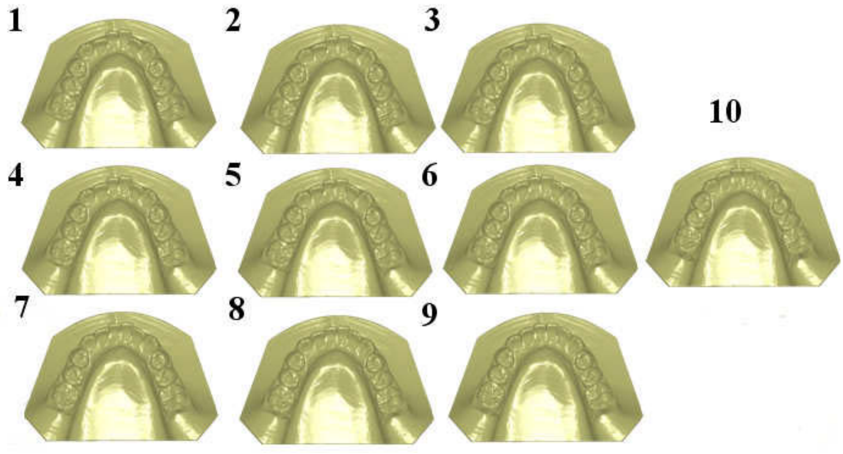

Fig. 10: Each step of setup model.

In order to validate our proposed method, a clinical test was performed. Fig. 11 shows the results of the treatment procedures of step 8 and step 10 that a dentist planned. For each step of the orthodontic planning, the physical plaster model can be manufactured by using 5-axis machining.

Fig. 11: Each step of physical plaster model.

Next, a clear aligner can be produced by vacuum forming of medical acrylic. Fig. 12 shows the result of a clear aligner produced by such a method.

Fig. 12: The result of vacuum forming.

Fig. 13: Clear aligner in a patient's mouth.

Fig. 13 shows the result of the clear aligner used in a patient's mouth. Unlike other methods, our clear aligner is built by vacuum forming, and the physical plaster model is milled using a 5-axis milling machine. The quality of the clear aligner is more smooth and refined than those models manufactured by rapid prototyping. Fig. 14 presents an error analysis of the teeth movement after the clear aligner was applied. This case is the result after a three-step treatment of the clear aligner. Compared to the un-fashioned teeth, the incisor has a maximum movement of about 0.7 mm.

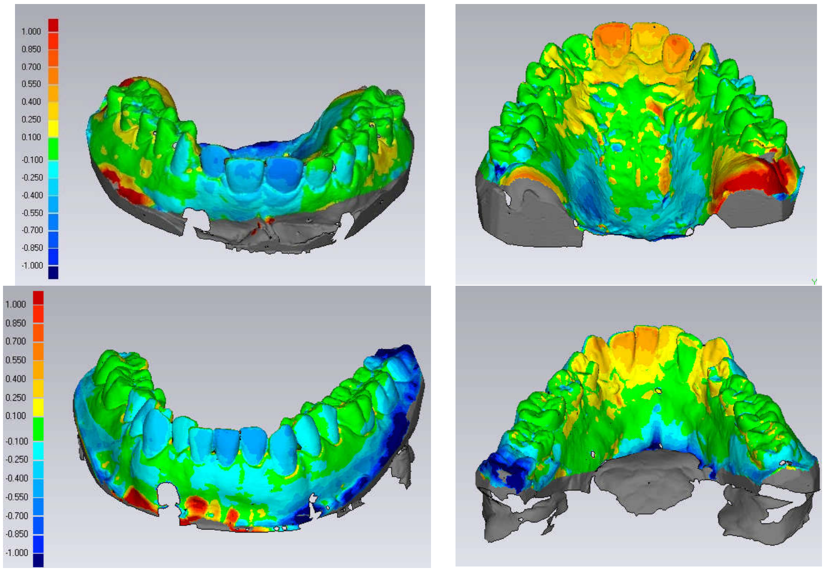

Fig. 14: Comparison of the third-step treatment compared with the original.

7. CONCLUSION

This paper proposed an efficient and convenient virtual teeth setup system for digital orthodontic treatment. The method this paper proposed includes three important steps: crown segmentation, gum deformation, and teeth collision detection. In our approach, we first digitize a plaster model into a virtual model. The virtual model can be separated into teeth and gum with our teeth segmentation method. In order to avoid creating gaps in a model, the virtual gum must deform with the teeth movement when the teeth are being adjusted. After the setup process is finished, a treatment device called a clear aligner can then be fabricated. The physical plaster model can be produced by using a 5-

axis milling process. The clear aligner is manufactured with vacuum forming using medical acrylics.

In addition, this system also integrates a force feedback device to improve the simulation result. A haptic device can yield a reactive force to prevent intersection when collision happens. A virtual teeth setup procedure is presented, which is efficient, user friendly and inexpensive compared with the traditional method. In the future, the goal for this research is to optimize the teeth set-up procedure to include movement of the teeth roots inside the alveolus. At present, we only showed the crown displacement in our setup procedure. If the teeth roots can be rebuilt precisely, collision between teeth roots and the alveolus can be avoided. Furthermore, only the reactive force of teeth collisions are currently simulated in our system. For accuracy, teeth movement inside the alveolus would be an important factor that could result in more accurate simulation.

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