A New Virtual Dynamic Dentomaxillofacial System for Analyzing Mandibular Movement, Occlusal Contact, and TMJ Condition

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Abstract. This paper describes a new virtual dynamic dentomaxillofacial system. Mechanical articulators have been used to reproduce mandibular movements and analyze occlusal contacts. With the help of VR and visualization technologies, virtual articulator systems can provide dynamic simulation and quantitative information visualization, enhance the functionality, and extend the system to additional application areas. We integrate mandibular movement simulation, occlusal analysis and TMJ analysis into our system, and design new algorithms to improve the results of analysis. This system is helpful to the education, the research, and the clinic in dentistry. An evaluation is conducted to prove the functionality and usability of the system.

Keywords: Visualization, Movement Simulation, Occlusion, Inter-articular Space.

1 Introduction

To simulate human mandibular movement is of great importance in dentistry. It can be used in diagnosing and evaluating the madibular movements, occlusal characteristics, the TMJ (tempromandibular joint) condition and other functions of the stomatognathic system.

Since introduced, mechanical articulators have been used to reproduce mandibular movements and analyze occlusal contacts. However, these mechanical devices have the following main disadvantages: 1. they cannot simulate the physiological mandibular movements; 2. they cannot provide time resolved information on the jaw movement; 3. they cannot visualize the real occlusal contact situation quantitatively and dynamically; 4. they cannot represent real dynamic condition of TMJ.

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In recent years, paramount progress is made in the area of computer graphics. With the help of VR and visualization technologies, it comes possible to build a more powerful mandibular movement simulation system. The computerization provides quantitative results dynamically and visually, enhances the functionality, and extends the system to additional application areas.

In this paper, we discuss a novel dynamic dentomaxillofacial system which satisfactorily integrates visualization, measurements, jaw movement simulation, occlusal analysis and TMJ analysis. Section 2 provides a brief survey of related research and previously developed systems. Section 3 discusses the process of data acquisition. Section 4 and Section 5 explain the main algorithms used in this system. Section 6 describes the system architecture and the user interface. We present our results and evaluations in Section 7.

2 Related Works

The computerized system for simulating the mandibular movements has been the focus of many studies. Hayashi et al firstly presented a computerized system to simulate mandibular movement and to visualize and analyze occlusion by measuring tooth shape with a 3D laser scanner and recording mandibular movement optically[1]. They made use of discrete 2D height-field data of tooth surfaces, and calculated minimal distances between points on opposing surfaces to generate occlusion. Okamoto et al reported a similar system that combined an optoelectronic tracking device for mandibular movements with a 3D contact-type digitizer for tooth shape[2]. This system could simulate dynamic occlusal situation and estimate occlusal contact area by exhaustively checking the distances from every point of the height-field to the points of the opposing surface. Kordass and Gartner developed the VR-articulator software tool—DentCAM using a 3D laser scanner and an ultrasonic measurement system[3]. This software allowed users to analyze static and dynamic occlusion as well as jaw relation. In addition, the movement paths of bilateral condylar points were simultaneously visualized which were in a sagittal and transversal view. However, all of the three systems did not mention the penetration between upper and lower teeth during the simulation. Because the skull model was not incorporated into these systems, the dynamic situation of the whole mandible (including the TMJ condition) cannot be visualized.

Enciso et al introduced computer methods to precisely visualize the movement of the whole mandible in 3-dimensions using CT data, digital models produced by destructive scanning, and mandibular motion capture[4]. Gallo et al presented a method of reconstruction and animation of the TMJ function using MRI data and jaw-tracking technology[5]. Dynamic intra-articulator space of the TMJ was computed and visualized in this system. Nonetheless, these two systems concentrated merely on analyze the dynamic condition of the mandible or the TMJ, rather than analyzing occlusal situation.

Based on the research noted above, we developed a novel dynamic dentomaxillofacial system, including the following functions: 1. simulating the movement of the whole skull, and providing time resolved information on the jaw movement; 2. producing various movement paths of arbitrary points on the mandible;

3. analyzing dynamic occlusal contact situation and the TMJ condition using a new method; 4. providing various 2D and 3D measurement tools.

3 Data Acquisition

The digital skull models are necessary to visualize the jaw movements on the screen. We create the 3D CT skull models from CT data. The skull of the patient undergoes CT scanning, and the digital CT data are transferred from the CT scanner to the computer using a CCD. The 3D skull model is reconstructed using the Marching Cubes algorithm. Thus the upper and lower jaw models are segmented, and stored in STL format. Afterwards, we reconstruct the digital dentitions by scanning the plaster models with the optical 3D measuring system. The upper and lower casts aligned in the relationship of ICP (intercuspal position) are scanned, and the digital upper and lower dentitions are then registered in ICP. Finally, the digital bone models are registered into the digital dentitions using an iterative closest point algorithm. The composite skull models with high detailed dental crowns are created, and exported for computerized manipulation.

Furthermore, we must measure the mandibular movement data for simulation of the patient's jaw motion. The ultrasonic-based system (ARCUS digma) is used to recording various jaw movements with six degrees of freedom[6]. This system measures the position of three sensors using four receivers according to the run times of ultrasonic impulses. In this system, the 3D positions of three virtual points (an incisal point, and both condylar points) in relation to the standard coordinate system are computed and stored sequentially with respect to time. In addition, the bitefork with the upper cast in its silicone occlusal registration is 3D scanned. By registering the composite skull models into the bitefork, the digital models and the motion data are combined in the standard coordinate system.

4 Visualization and Measurements

We utilize the Visualization ToolKit (VTK) and OpenGL to provide 3D data visualization. The system reads in the 3D models generated from the scan data, and provides various tools for users to browse, measure and inspect the whole skull conveniently. These tools include 2D/3D measurement tools, clipping planes and specific plane visualization, as shown in Fig. 1.

Distance and angle measurements are provided both in 2D and 3D, clearly distinguished from each other by different colors and notations. Users can simultaneously perform multiple measurements on the models. The measurements keep updating during the motion playback, providing a dynamic view of the statistics which users are concerned about.

Also users can easily create a clipping plane along arbitrary direction, so as to inspect and measure concealed anatomical structures. The system enables users to freely perform measurements on the clipping plane, thus a large number of anthropometric parameters of the occlusion, anatomy, orthodontics, and orthognathic surgery can be measured, which are applicable in operation planning. In addition,

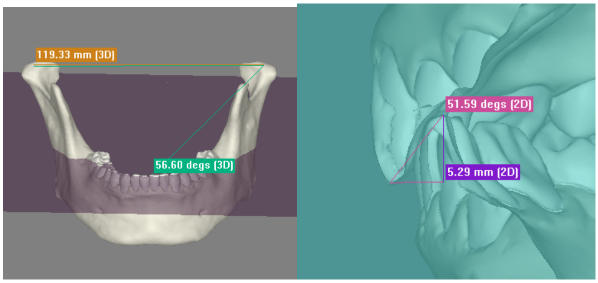


Fig. 1. 2D/3D measurement tools, the clipping plane (cyan) and specific plane visualization (magenta). Different colors are used to distinguish different measurements.

users can define and visualize a specific plane by picking three points that are supposed to be on the expecting plane. It can be used to visualize imaginary planes, such as occlusal plane and Frankfort plane. These planes can be acted as reference planes during the measurements.

5 Jaw Movements and Occlusions

5.1 Movement Simulation

We build a parser to read in the text data file exported by ARCUS Digma. The parser separates the motion data of each movement, and groups them distinctively for further processing. Each group contains coordinate sequences of two condylar points and the incisal point during one movement. The system converts the coordinate sequences into transformation matrix sequences, which are later used for movement simulation.

Users are allowed to select from seven separate movements, pause or continue the playback, and freely navigate throughout the motion playback using a video control panel (the toolbar below the menu in Fig. 2). Several time-related parameters are visualized by the playback, such as the chewing cycle, the motion velocity, and the timing of the mastication.

5.2 Motion Paths

The system provides users with various movement paths of arbitrary mandibular points, including the kinematic center points, and any points that users designate on the mandible (Fig. 3). The system calculates the movements of the points throughout the recorded motions, and generates a movement path in 3D for each of them. These paths can be browsed, measured and monitored as the models can, and the system automatically keeps the consistency between the paths and the models in real time. By measuring these paths, many distances and angles were provided, such as ranges of movement, opening angle, shift angle. All of these parameters can be used to analyze the motion of the condyles and specialized points.

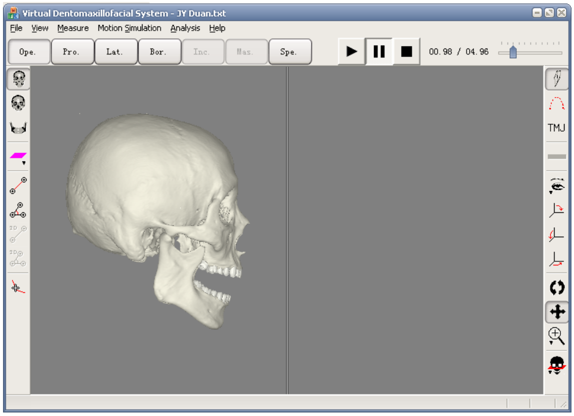


Fig. 2. The user interface of the system. Video control panel is positioned below the menu.

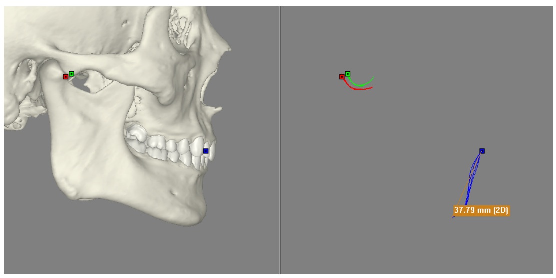


Fig. 3. Motion path visualization. The points tracked are indicated by the square markers (on both sides). Users are also enabled to perform measurements on the tracks.

5.3 Real-Time Occlusal Analysis

We improve Hayashi's method to perform real-time occlusal analysis[7]. The system resamples tooth surfaces into uniform 2D height-field grids, and calculates minimal distances between grid points on opposing surfaces to generate occlusion (Fig. 4). In addition, we check whether the opposing point falls below the current point, which indicates an occurrence of penetration. By this means all penetrations are checked and can be precisely reported, allowing users to make the decision how to treat the error introduced by the penetrations. The grid resolution can be adjusted to take the tradeoff between precision and the response time, which allows users to monitor the changes of the occlusion while browsing through the motion playback, and analyze the order and the timing of the occlusal contacts.

5.4 Accurate Occlusal Analysis and TMJ Analysis

As a result of the compromise, the real-time occlusal analysis algorithm gives only less-detailed version of the occlusion, and has distinct limitation because of its 2D

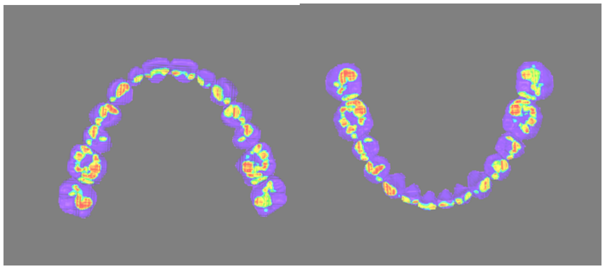
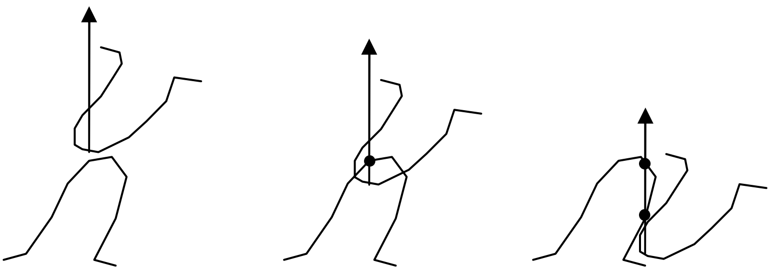


Fig. 4. Real-time occlusal analysis results. Inter-surface distances are indicated by different colors.



(a) No intersection. No penetration.

(b) One intersection. Penetration.

(c) Two intersections. No penetration.

Fig. 5. Penetration checking algorithm. Different situations are illustrated by (a), (b) and (c).

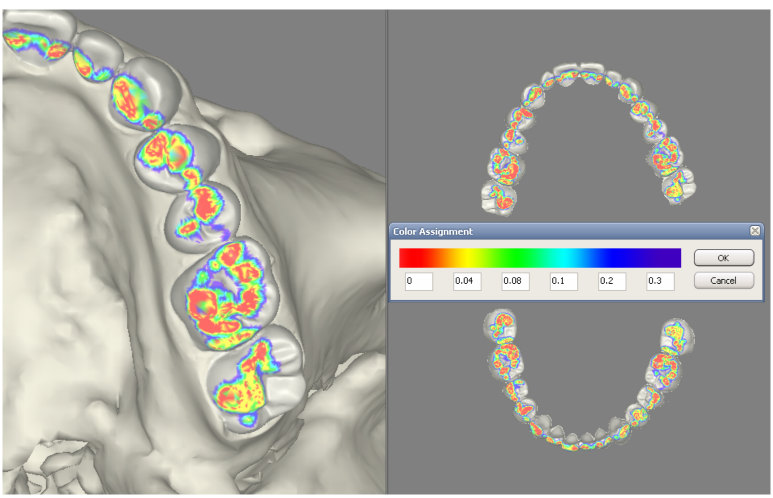


Fig. 6. The results of accurate occlusal analysis and the color assignment dialog

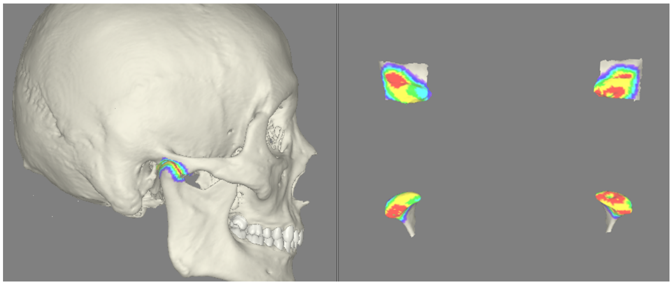


Fig. 7. TMJ analysis results

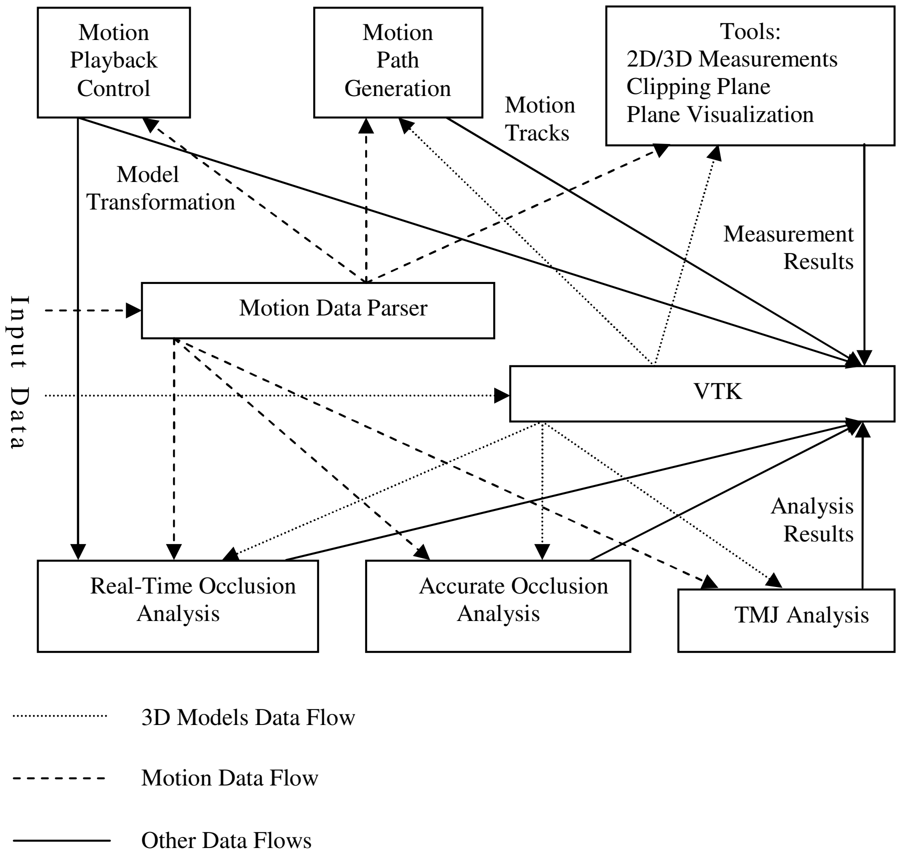


Fig. 8. System architecture

height-field assumption[7]. To provide users with more comprehensive and detailed information, we design another occlusal analysis algorithm that is more time-consuming but gives better results.

The algorithm consists of two stages: the penetration checking stage and the distance calculation stage.

In the first stage, we traverse all vertices of the teeth models and determine whether a vertex penetrates into the opposing model. This is done via the following steps:

1. Shoot a ray from the vertex in question along the direction away from the opposing model;
2. Check the ray with the opposing model for intersections;
3. If the number of intersections is odd, the vertex in question is considered penetrating the opposing model.

Some examples are provided in Fig. 5 to illustrate the algorithm of this stage.

In the second stage, the system looks for a nearest vertex on the opposing model for each vertex that is not considered as a penetration. The distance to the nearest vertex is stored, and later used to generate the occlusion by assigning colors to different ranges of distances (Fig. 6). The occlusion on the models can be browsed and measured with the model, and the details and concealed areas of occlusion can be explored by zooming in and using clipping planes. The results provided are helpful for evaluating occlusal dysmorphology and designing dental prostheses with functional occlusal surfaces.

As an extensive application, the new algorithm can also give satisfactory results in TMJ analysis (Fig. 7). We use fossae and condyles models instead of teeth models, and assign colors to larger distance ranges to visualize interarticular space. Thus the users can analysis and diagnosis of the TMJ condition according to the relation between the joint space and the loading.

6 System Integration and User Interface

Fig. 8 shows the architecture of the system.

All the functions provided are satisfactorily integrated in the system, and can be smoothly switched using the toolbars around the view. Various visual cues are provided in order to guide users in 3D operations, such as trackball rotation[8], and further improve the performance of the user interface.

In addition, users are allowed to use 3D mice for navigation if available. Users can navigate with a 3D mouse in the non-dominant hand, while operating on the models with the usual pointing device (mouse, for example) in the dominant hand, according to the concept of two-handed interaction[9]. All these techniques are employed in order to build a more efficient, intuitive and natural user interface.

7 Results and Evaluations

Our system can be used to analyze mandibular movements, occlusal contacts and TMJ situation. All of these functions are helpful to dental education because many conceptions and parameters in dentistry become intuitionistic. In addition, many quantitative data are also provided in our system, which benefit dental research. As far as dental clinic is concerned, this system assists diagnoses and therapies, and monitors the develop of diseases. We invited ten specialists among the dentists to perform an evaluation. After a period of trial, the subjects were surveyed on the degrees of satisfaction of the functions and the interface of our system. The results are presented in Table 1. It is revealed that our system is sufficient for the education, the research, and the clinic in dentistry.

Table 1. Evaluation results

	The degrees of satisfaction				
	1	2	3	4	5
Movement Simulation					10
Specific Plane Visualization			2	6	2
Clipping Plane			4	6	
2D/3D Measurement			6	4	
Motion Paths				1	9
Occlusal Analysis				5	5
TMJ Analysis			2	7	1
Accuracy			1	7	2
System Integration and User Interface				8	2
Overall				7	3

8 Conclusion and Future Work

In this paper we present a new virtual dynamic dentomaxillofacial system. We integrate mandibular movement simulation, occlusal analysis and TMJ analysis into a single system, and design new algorithms to further improve the results, as shown in the figures. We also perform an evaluation to prove the functionality and usability of the system.

Our future work includes employing the Marker-controlled Perception-based Mesh Segmentation algorithm to enhance the speed and fineness of the occlusal analysis[10], and researching on utilizing this system to assist virtual implant.

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