

Research Article

The Research and Development on Simulation of Oral Cavity Food Chewing System

Xiaoming Zhang and Min Hui

Department of Prosthodontics, Binzhou Medical University Hospital, Binzhou, Shandong, 256603, China

Abstract: This paper aimed to dig the destruction effect of change rules of oral cavity chewing system for food and the significance of relationship between chewing movement and chewing effect for the understanding of food quality and structure features. The process and effect of chewing movement for crushing food was stimulated and analyzed by reverse engineering technology combined with modern dental theory. The experiment results of uniform motion model and variable motion model showed that in grinding mode, a higher chewing rate had good effect on the destruction of the food and influence of acceleration change on chewing effect was relatively weak, in which uniform acceleration and deceleration motion was more suitable for grinding the elasticity and toughness of food.

Keywords: Chewing system, oral cavity, simulation

INTRODUCTION

Chewing is one of the important physiological functions of oral cavity, which plays an important role in maintaining and promoting a healthy stomatognathic system. With the development of science and technology, external simulation approach on the function of mouth chewing system is gradually turned from the simulation of simple pounding action to the simulation of complex dental action cycle. Chewing system is reflective activities composed of shrinking successively to simulate chewing muscles. However, human chewing behavior is a very complex biological movement process. People developed a variety of chewing simulators in order to study the chewing system. Wei and Yang (2013) studied whether simulation material had enough mechanical performance, whether it met the quality requirements of dental material and analyzed application prospect of chewing simulator from multiple perspectives. For the biomechanical characteristics of the driver muscle in human mandible system were asymmetric distributed, different directions of the force and upper and lower jaw's connection points were not coplanar. Cong *et al.* (2013) *et al* put forward a new type of imitation of mandibular movement robot that can satisfy the requirement of authenticity on human chewing action crushing food. Yu *et al.* (2013) compared patients with individual normal temporomandibular joint vibration and masticatory muscle electromyography activity characteristic, analyzed and summarized the characteristics of chewing activity.

The research conclusion of this article was established on the basis of these assumptions and the bionic dental model was reconstructed using the reverse engineering technology (Sun and Wang, 2014). The motion model of chewing food was constructed by using numerical simulation method. The chewing movement in different masticatory mode was simulated and the influence of the chewing movement for chewing effect was analyzed on this basis, which provides a convenient method for further research on the relationship between chewing movement and food texture (Wang *et al.*, 2014). It is of a guiding significance to the research on movement rules of chewing equipment.

MATERIALS AND METHODS

General materials:

The obtaining of teeth point cloud data: Stomatognathic system of healthy adult male was taken as sampling specimens and tomography was done to the subjects from the bottom of the mandible to the bottom of the nasal bones by using light speed d spiral CT scanner of American GE company. Scanning pitch was 1.375 mm; layer thickness was 0.625 mm with the interval of 2.5 mm, a total of 239 pcs two-dimension CT image data of oral cavity structure were obtained. The entire CT tomography images were imported in mimics10.0 for three-dimensional restructuring. The reorganized image was extracted with threshold segmentation and region feature. Point cloud data of maxilla dentition and mandible dentition were obtained, as shown in Fig. 1.

Corresponding Author: Min Hui, Department of Prosthodontics, Binzhou Medical University Hospital, Binzhou, Shandong, 256603, China

This work is licensed under a Creative Commons Attribution 4.0 International License (URL: <http://creativecommons.org/licenses/by/4.0/>).

Table 1: The simulation parameters of food materials

Elasticity modulus	Poisson Ratio λ	Density $\rho/(g/cm^3)$	Kinetic friction Coefficient e
E/Mpa	0.35	1.0	0.2

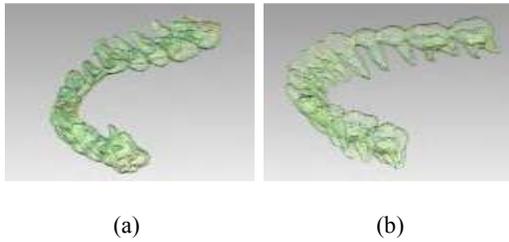


Fig. 1: Teeth point cloud data (a): Maxilla dentition point cloud; (b): Mandible dentition point cloud

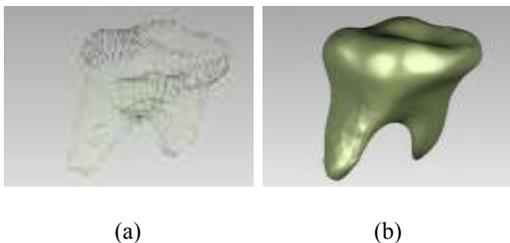


Fig. 2: The reconstruction of three-dimensional model of molar in maxilla; (a): Point cloud data; (b): Three-dimensional model

The reconstruction of teeth three-dimensional model: The point cloud data obtained from threshold segmentation was filtered, cut and repaired; the point cloud model of single tooth was isolated (Zhu *et al.*, 2014). Figure 2a was point cloud model of the first molar in maxilla. Point cloud that was repaired complete were encapsulated into a polygon and then repaired, smoothed the polygon. The curvature characteristic curve of polygon surfaces was extracted, the surface grid was divided and finally the three-dimensional model of teeth was reconstructed using NURBS surface fitting method (Chen *et al.*, 2014). Figure 2b is the first molar model in maxilla obtained from the reconstruction of reverse engineering, as shown in Fig. 2.

The constitutive model parameters of food materials:

Classification of food additives: Constitutive features of food material are generally complex, but the mechanical characteristics of most of the foods are close to the linear elasticity before the occurrence of broken. This research assumed food material as isotropic material with isotropy and linear elasticity based on the elastic-plastic mechanics theory. The parameters of the simulated material the study set is shown in Table 1. The parameters of most of the grain cereal ingredients are close to it (Liu and Wen, 2010).

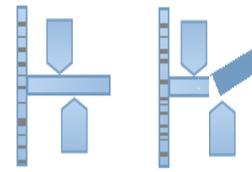


Fig. 3: Diagrams of simplified cutting movement

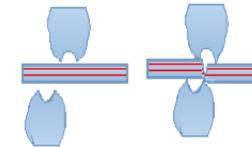


Fig. 4: Diagrams of simplified pestle pressure

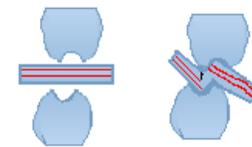


Fig. 5: Diagrams of simplified grinding movement

Methods:

Cutting mode: Cutting model simulated the movement process of teeth cutting food. According to the parameters given in Table 1, the food block size was $8 \times 8 \times 1$ mm, the incisor teeth had 1 mm relative motion in the horizontal and vertical direction with the simulation time of 0.2 s. Cutting and biting food is the initial stage of chew. One end of the material was fixed (when cutting and biting food, food is usually taken by hand to prevent its movement). One limit baffle was added in the middle of the food block (the incisor tooth restricted the sliding of food) and the other end of the food began to transform by the effect of shear force of incised tooth, as shown in Fig. 3.

Pestle pressure mode: According to the parameters given in Table 1, the size of food block cut down by incisor teeth was $8 \times 8 \times 1$ mm, the molar had 1 mm relative motion in the vertical direction with the simulation time of 0.2 s. This paper simulated the movement process of pestle pressure of molar on food, which needed to crush it into smaller food particles using the molar. The top of the food block was supported in static state by highlight parts of molar and the bottom of the block was beginning to fracture under the pestle pressure of lower cusp (the lower cusp extruded food to the upper tooth socket), as shown in Fig. 4.

Grinding mode: In grinding mode, the destruction of chewing for the food was made up of comprehensive effects caused by extrusion, shear, tear, friction of upper and lower teeth face to the food. According to the

parameters given in Table 1, the size of food block was 8×8×1 mm, the molar had 1 mm relative motion in the horizontal and vertical direction with the simulation time of 0.2 s. When food block was squeezed into small particles, molar teeth started to grind, crush food. In the initial stage, the material was in stationary state by upper and lower teeth clamping and then the fluctuation of upper and lower teeth surface began. It is shown in Fig. 5.

RESULTS AND DISCUSSION

The effects of chewing rate: Here, we simplified the chewing movement into four models: uniform motion (Luo, 2014), uniform acceleration and deceleration motion, mean saltus movement (Liu, 2010) and simple harmonic motion (Wang, 2014). Tooth chewing movement was simplified as uniform motion pattern, namely the lower teeth accelerated to V_0 in a very short period of time (this period of time was ignored), then it came into contact with food gradually at speed of V_0 and began to squeeze the food. For any time t , relative displacement s of the lower teeth surface of mandible in uniform chewing process can be represented by Eq. (1):

$$s = V_0 t = \frac{S_0}{T_0} t \quad t \in [0, T_0] \quad (1)$$

S_0 represented relative displacement between the upper and lower teeth in one chewing movement, T_0 represented the total time of chewing movement.

Different chewing speeds were adopted respectively under the three kinds of chewing modes to simulate for chewing movement. S' was total displacement vector of horizontal and vertical direction,

σ MAX was maximum principal stress, Tresca was shear stress, Mises was dense seth stress. Simulation results were shown as Table 2 to 4,

From Table 2 and 3, we can know that pestle pressure movement had a larger shear stress and Mises stress under the condition of the displacement vector and low cutting movement (He *et al.*, 2011). This also explained why people tend to use molar teeth to crush hard food.

From Table 2 and 4, we can know grinding movement had a larger shear stress and dense seth stress than cutting movement under the condition of the same movement rate and relative displacement. This showed that the grinding movement can have good effect on crushing elasticity and toughness of food. In addition, we found that cutting movement can produce larger principal stress, which indicated incisor was suitable for chewing brittle food.

We can conclude from Table 4, with the increase of chewing rate, chewing effect was basically in the rise trend, but rate did not affect the chewing effect all the time. When $T_0 = 0.3$ s, shear stress and Mises stress was the largest; when $T_0 = 0.2$ s, shear stress and Mises stress was drop. This explained that the bigger of the rate of uniform motion in a certain range, the better it was when grinding elasticity and toughness of food. There have been some research on the relation of material compression rate and fracture effect; the study suggested that the relationship between the rate and the damage effect were positively correlated:

- **Uniform acceleration and deceleration model:** Lower teeth first moved to upper teeth surface in the form of uniform acceleration and then the upward movement continued in the form of uniform deceleration until the upper and lower teeth face bite together when rate reached zero. For any time t , displacement s can be expressed by Eq. (2):

Table 2: The influence of rate to cutting effect

S'/mm	T0/s	V0/(mm/s)	σ max/MPa	Tresca/MPa	Mises/MPa
1.41	0.5	2.83	6.45	10.78	9.44
1.41	0.4	3.54	6.39	10.79	9.45
1.41	0.3	4.71	6.48	10.83	9.49
1.41	0.2	7.07	6.27	10.70	9.39
1.41	0.1	14.14	6.16	10.85	9.53

Table 3: The influence of rate to pestle pressure effect

S'/mm	T0/s	V0/(mm/s)	σ max/MPa	Tresca/MPa	Mises/MPa
1.0	0.5	2.0	3.45	11.13	10.49
1.0	0.4	2.5	3.52	11.11	10.48
1.0	0.3	3.3	3.64	11.15	10.51
1.0	0.2	5.0	3.72	11.17	10.54
1.0	0.1	10.0	3.72	11.16	10.53

Table 4: The influence of rate to grinding effect

S'/mm	T0/s	V0/(mm/s)	σ max/MPa	Tresca/MPa	Mises/MPa
1.41	0.5	2.83	5.41	15.70	13.90
1.41	0.4	3.54	5.56	15.78	13.97
1.41	0.3	4.71	5.46	16.07	14.20
1.41	0.2	7.07	5.44	15.49	13.79
1.41	0.1	14.14	8.64	15.13	13.58

$$s = \begin{cases} \frac{S_0}{T_0 T_1} t^2 \\ \frac{T_0 S_0}{T_0 - T_1} \left(\frac{2}{T_1} t - \frac{1}{T_0 T_1} t^2 - 1 \right) \end{cases} \begin{matrix} t \in [0, T_0] \\ t \in [T_1, T_0] \end{matrix} \quad (2)$$

S0 represents relative displacement between the upper and lower teeth face in one chewing movement, T0 represents the total time of chewing movement.

- **Mean saltus movement model:** The lower teeth surface first did acceleration motion in the form of acceleration decreasing and then did deceleration motion in the form of acceleration gradually increasing. For any time t, displacement s can be expressed by Eq. (3):

$$s = \frac{S_0}{T_0^2} \left(3t^2 - \frac{2}{T_0} t^3 \right) \quad t \in [0, T_0] \quad (3)$$

S0 represents relative displacement between the upper and lower teeth face in one chewing movement, T0 represents the total time of chewing movement.

- **Simple harmonic motion:** The lower teeth first did cosine acceleration motion, then did cosine deceleration motion. When the speed was zero, the upper and lower teeth chewed together. For any time t, displacement s can be expressed by Eq. (4):

$$s = \frac{S_0}{2} \left(1 - \cos \left(\frac{\pi}{T_0} t \right) \right) \quad t \in [0, T_0] \quad (4)$$

S0 represented relative displacement between the upper and lower teeth face in one chewing movement, T0 represented the total time of chewing movement.

Under the three kinds of chewing modes, chewing effect was simulated when chewing acceleration was changed. S' was total displacement vector of horizontal and vertical direction, σMAX was maximum principal

stress, Tresca was shear stress, Mises was Mises stress. Stimulation results were showed in Table 5 to 7.

We can conclude from Table 5 to 7 that stress concentration values produced by different motion modes of food material were close, which explained that the influence of the change of the acceleration for chewing effect was relatively small; the effect on pestle pressure mode can be ignored nearly. But in grinding mode, shear stress and Mises stress of acceleration and deceleration movement were the greatest, simple harmonic motion was next, relatively sharp mean saltus movement stress concentration of acceleration change was minimum. This showed stable acceleration can play a better grinding crushing effect. When grinding food with strong chewiness, the acceleration and deceleration movement was more appropriate.

Discussion: Because of the complexity of the chewing movement, the article put forward three hypotheses in the simulation analysis:

- Chewing was a process that the maxillary and mandible teeth closed together after mandible teeth surface contacted with the food material. The destruction of chewing food mainly occurred at this stage, the influence of other period shall not be considered.
- In the process of chewing, the food material only occurred because of the physical change of acting force of tooth surface, in which the warming effect of friction on material and heat conduction effect were not considered and the same as all the chemical reactions.
- Temperature, humidity of oral cavity and its effect on mechanical properties of materials can be ignored. Research conclusion of this paper was established on the basis of these assumptions.

Human molars (Liu *et al.*, 2014) and incisor model were reconstructed using reverse engineering technology. The simplified model of chewing

Table 5: The influence of acceleration on the cutting effect

Mode of motion	S'/mm	T0/s	σ max/MPa	Tresca/MPa	Mises/MPa
Uniform acceleration and deceleration	1.41	0.2	6.37	10.73	9.39
Mean saltus	1.41	0.2	6.37	10.73	9.41
Simple harmonic quantity	1.41	0.2	6.37	10.73	9.49

Table 6: The influence of acceleration on the pestle pressure effect

Mode of motion	S'/mm	T0/s	σ max/MPa	Tresca/MPa	Mises/MPa
Uniform acceleration and deceleration	1	0.2	3.71	11.16	10.53
Mean saltus	1	0.2	3.72	11.16	10.53
Simple harmonic quantity	1	0.2	3.70	11.16	10.53

Table 7: The influence of acceleration on the grinding effect

Mode of motion	S'/mm	T0/s	σ max/MPa	Tresca/MPa	Mises/MPa
Uniform acceleration and deceleration	1.41	0.2	6.03	15.64	13.86
Mean saltus	1	0.2	6.55	15.29	13.69
Simple harmonic quantity	1	0.2	7.26	15.57	13.85

movement was established according to the physiology rules of chewing movement. The chewing destruction process of food was simulated using numerical simulation method. The simulation analyzed the effect of the chewing rate and the acceleration for chewing and crushing food. Research showed that: when the mandible did uniform motion and chewing rate increased in a certain range, the growth trend of shear stress and Mises stress of grinding motion was obvious higher than cutting motion, which illustrated that grinding movement was more suitable for crushing elasticity and toughness; stable chewing acceleration will produce relatively strong concentration stress; when the grinding elasticity and toughness were not easy to crush food, uniform acceleration and deceleration motion can produce larger shear stress and Mises stress.

ACKNOWLEDGEMENT

Shandong Education Commission, Project Number: 3120.

REFERENCES

- Cong, M., T.Z. Liu, H.Y. Wen, J. Du and W.L. Xu, 2013. Design and kinematics performance analysis of a novel jaw movement robot. *ROBOT*, 2(35): 239-248.
- Chen, L., Y.M. Sun and G.P. Xie, 2014. Chewing process analysis based on the discrete element method. *J. Jilin Univ., Med. Edn.*, 5: 1517-1524.
- He, Y.J., Y. Zhu and H.J. Liu, 2011. Analysis of the von mises stress fields generated by a pulsed line-source laser in metal pipes. *Laser J.*, 32(5): 38-38.
- Liu, L., W.L. Chen and Y. Cui, 2014. Orthodontic treatment of multi-tooth scissor crossbite. *Chin J Pract. Stoma.*, 8: 454-458.
- Liu, Z.Y. and J.H. Wen, 2010. The measure and study on the elastic modulus of soybean. *Grain Stor.*, 3: 27-30.
- Luo, L.X., 2014. Phase wave and phase coincidence theory of uniform motion particle. *College Phy.*, 9: 2.
- Liu, X.X., 2010. Structure of jerk-continuous cam curve suitable for special requirements. *Heavy Mach.*, 5: 46-51.
- Sun, Q.Y. and J.D. Wang, 2014. Reverse engineering technology in mould design and manufacturing. *Tech. Innov. App.*, 21: 111.
- Wei, Y.H. and M. Yang, 2013. Design and application progress of chewing simulator. *J Oral Sci. Res.*, 9: 34.
- Wang, Y., H.Y. Yang, W.W. Hou and Z.L. Zhu, 2014. Exploration and practice of effective teaching in physical properties of foods course. *Time Edu.*, 1: 62.
- Wang, L., 2014. The determination of simple harmonic motion. *Human Mid. Sch. Phys.*, 9: 63
- Yu, Z., X.Y. Wang and Y. Zhao, 2013. Class II division 2 malocclusion patients temporal mandibular joint vibration and masticatory muscle electromyography activity characteristics. *J Oral Sci. Res.*, 9: 20.
- Zhu, J., L. Yang, W.X. Liu and C.X. Xiao, 2014. Significant features of keepingpoint cloud model scale. *J. Comput. Aided Design Grap.*, 10:1624.