DEVELOPMENT OF THE SUPPORT SYSTEM FOR INDIVIDUAL STRESS ANALYSIS OF A BONE

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1. ABSTRACT

This paper presents a new support system of setting boundary conditions for individual stress analyses. The individual modeling has become a significant technique in computational biomechanics. However, implementation of the stress analyses requires a lot of time because of difficulty in setting the boundary conditions. We discuss necessary functions for speedy individual simulations and develop the support system that satisfies the functions. The realized functions are as follows; selection of nodal points on muscular attachment sites, dispersion of the muscular forces, setting of the direction of the muscular forces and calculation of the reaction forces around a joint portion. This paper also discusses estimation of muscular forces on the viewpoint of effective setting of boundary conditions. Three kinds of objective functions are provided and evaluated by comparison of the computed stress distributions. The developed system is applied to the human mandible for the validity of the performance.

2. INTRODUCTION

Individual modeling is a significant technique for examination of biomechanical characteristics of living bodies. Several research groups including us have proposed the modeling methods to generate finite element models of bones. As the modeling methods serve noninvasively accurate models for computer simulations, it will greatly contribute to clinical diagnosis or medical treatment in the near future. For the contribution to the clinical fields, it is critical to shorten the required time for individual simulations. Figure 1 shows procedures for performing an individual stress analysis of a bone. Among the procedures, automated modeling is an important function to shorten the required time. The authors proposed automated modeling method by use of Delaunay triangulation, which requires a little working time. However, there are still two factors to be discussed for quick individual simulations.

One is the function to set up boundary conditions to the FE model for stress analyses. In the musculoskeletal system, nodal points corresponding to restricted portions are fixed and those corresponding to muscular sites sustain distributed forces. General purposed software tools called pre-post processors have such a function of setting boundary conditions. However, these ready-made tools are not suite for analyses of bones and it usually takes a lot of time to set up the conditions. To solve the problem, we make conceptual design of the new system and propose the concrete functions that easily set up boundary conditions for biomechanical analyses. The details are described in the chapter 3.

Key words: Stress analysis, Individual model, Boundary condition, Muscular force

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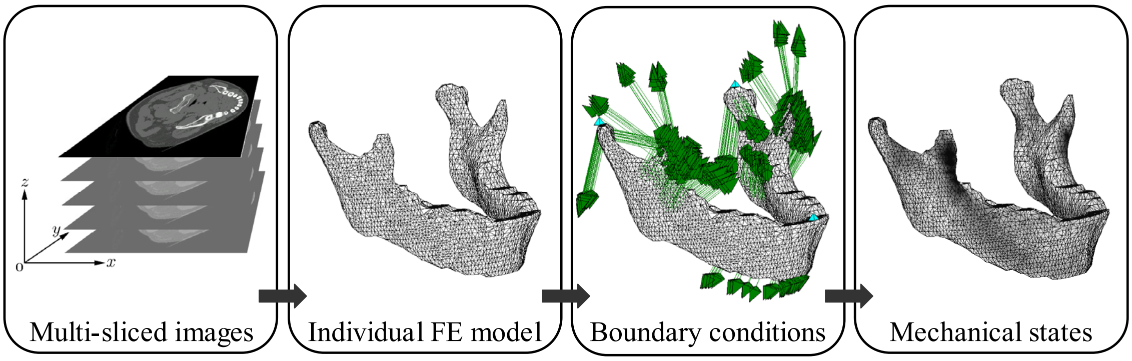


Fig.1 Procedure of individual stress analysis

The other factor required for speedy simulations is the method to estimate the muscular forces in the musculoskeletal system. Living bones are usually affected by multiple muscles. To execute stress analyses of any musculoskeletal system, we must determine definite values of the muscular forces. In our biomechanical studies, a medical collaborative researcher estimates ratios of muscular forces acting on the human mandible based on an anatomical knowledge. This is a difficult operation even for a medical expert, and the operation takes a lot of work and time. On the point of estimation om muscular forces, many studies have been reported. Almost of them discuss muscular forces in musculoskeletal movements, however, there are few studies from the viewpoints of effective individual simulations. We discuss it in the chapter 4.

3. DESIGNS AND DEVELOPMENT OF THE SUPPORT SYSTEM

In stress analyses of a living bone, muscular forces have to be distributed to specified nodal points of the model. Furthermore, the bone is usually connected to another one through a joint portion and affected by a reaction forces. Taking into account of these points, we developed the supporting system for setting boundary conditions of bone. The system has a visual interface for easy operation and is applicable to a variety of bones though this study is focused on a human mandible. We describe the details of the four special functions as the following sections.

3.1 Selection of nodal points on muscular attachment sites

Bones in the living body usually receive internal forces by activation of muscles. Therefore, it is necessary for the support system to select specific nodal points of the FE model and to assign proper loads to them. The proposed system displays the individual model in the arbitrary direction which an operator assigns using a mouse. Target nodal points are selected by dragging the mouse on the screen. As the nodal selection is performed for each muscle, the operator is able to concentrate the task.

3.2 Dispersion of the muscular forces

Recent our study has proposed a new modeling method to control size of elements according to complexity of shape for each part in a bone [1]. Figure 2 (a) shows the example of a human mandible generated by our modeling method. Here, we should pay attention to the size of elements in the stress analyses because improper stresses may cause. Figure 2 (b) shows an equivalent stress distribution when forces are equally given to nodal points corresponding to the temporal muscle. The computed result shows

large stresses at portions divided by small size of elements.
To avoid the improper stress concentrations, we added a function that automatically controlled the loading forces so that muscular forces equally acted on the specified part. The proposed supporting system calculates a loading force for each nodal point in proportion to the mean value of surface areas of the elements around the nodal point when areas of the load are specified. Figure 2 (c) shows the stress distribution with this function. The function decreases stress concentrations at the places where are divided by small size of elements.

3.3 Setting the direction of the muscular forces

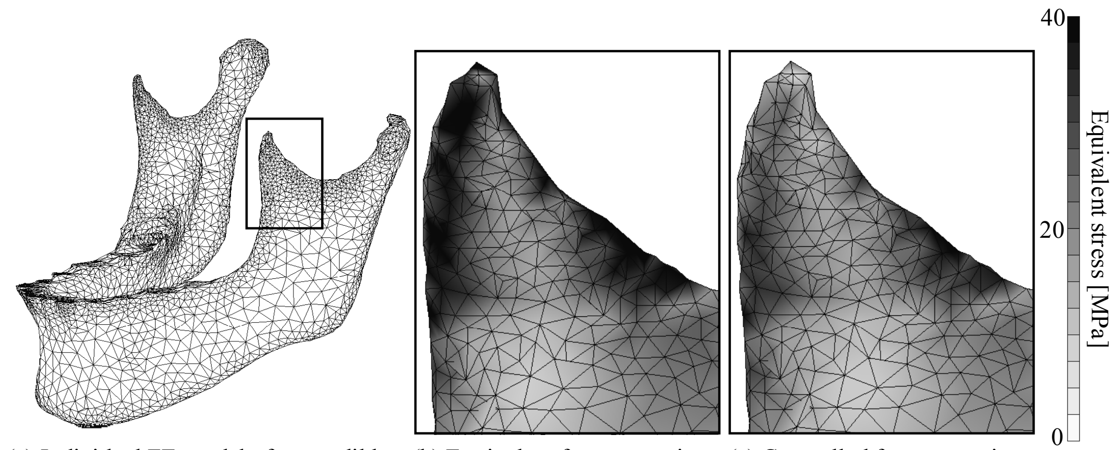
The proposed system displays the target model and the auxiliary object simultaneously in the arbitrary direction. This function enables us to easily set up the exact vectors of muscular forces as we can visually check the moving end and the fixed end of the muscles on a computer screen. Figure 3 shows a computer screen in setting the direction of a muscular force. The system displays the model with an auxiliary object which connects to the opposite side of muscles. In case of the human mandible, the system displays mandibular shape with the maxillary bone.

3.4 Calculation of the reaction forces at condyles

The finite element method requires constraint points for restriction of rigid motion. From viewpoints of *in vivo* biomechanical study, it is desirable to minimize the number of constraint points. However, few constraint points may cause stress concentration.
In case of our study of the human mandible, we use the mechanical condition as illustrated in Fig. 4. Two constraint points are set at the top of condyles. The reaction forces are computed by consideration of moment balance around an axis of the two constraint points, and the forces are equally distributed on the adjacent nodal points on each condyle. The proposed support system automatically calculates the distribution of reaction forces whenever we give a boundary condition to the model.

3.5 Performance of the support system

Our previous studies took a lot of time to set up the boundary condition compared with the individual modeling or the stress analysis [2]. To compute a stress distribution of human mandible in occlusion, it had taken ten hours or more to set up boundary



(a) Individual FE model of a mandible (b) Equivalent forces are given (c) Controlled forces are given

Fig.2 Dispersion of the muscular forces

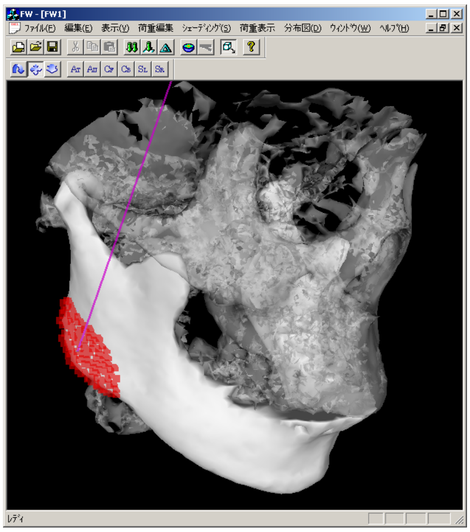


Fig.3 Overview of the proposed system

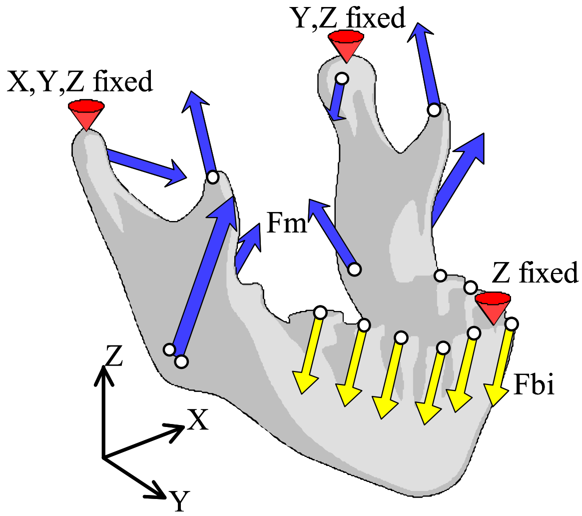


Fig.4 Boundary condition of human mandible

conditions with the conventional way. Proposed system shortens the required time less than an hour. Consequently, the system is possible to analyze multiple stress performs modifying the boundary conditions such as change of muscular directions or attachment sites of muscles.

4. ESTIMATION OF MUSCULAR FORCES

4.1 The method to estimate muscular forces

Estimation of muscular forces for application to individual stress analyses is performed by the following four steps.

Firstly, attachment sites of the muscles and the muscular directions are set to the model using the support system as described in the section 3.1. In case of the human mandible, reaction forces on the teeth are set up as outer forces.

Secondly, muscular forces are computed under the moment balance of the model when activity rates of muscles are given. The activity rates are set to be appropriate values in the initial state, later they are calculated by the step 4. In case of masticatory system, moment balance is adjusted around the axis along two condyles of the mandible (x-axis) using the following equation.

$$\sum\left(\mathbf{C}_b^x \times \mathbf{F}_b\right) + \alpha \sum\left(\mathbf{C}_m^x \times \mathbf{f}_m\right) = 0 \qquad (1)$$

where, $\mathbf{F}_b$ is a vector of a reaction force at the teeth, $\mathbf{C}_b^x$ and $\mathbf{C}_m^x$ are vectors from the x-axis to the loading points on the teeth and attachment sites of muscles. $\mathbf{f}_m$ denotes a vector with the activity rate of a muscle, α is a proportionality constant. That is, the magnitudes of muscular forces are calculated by adjusting the moment balance of the model.

Thirdly, the reaction forces acting on the joint portions are calculated. In case of the mandible, the following equation is used.

$$\mathbf{F}_{r1} + \mathbf{F}_{r2} + \sum \mathbf{F}_b + \sum \alpha \mathbf{f}_m = 0 \qquad (2)$$

where, $\mathbf{F}_{r1}$ and $\mathbf{F}_{r2}$ are reaction forces at the both condyles.

Finally, activities of muscles are estimated using an optimization method. In this study, we provide the following three kinds of objective functions composed of two parts and minimize them.

(a) Summation of muscular forces + Moment around saggittal axis
(b) Summation of square of muscular forces + Moment around saggittal axis
(c) Summation of third power of muscular forces + Moment around saggittal axis

The method is represented by minimization of the next objective function in case of n = 1, 2 and 3. The minimization is resolved by the steepest descent method under the condition that all muscular forces are positive.

$$I = \sum \left(\alpha \left|\mathbf{f}_m\right|\right)^n + k\left(\sum\left(\mathbf{C}_b^y \times \mathbf{F}_b\right) - \sum\left(\mathbf{C}_m^y \times \mathbf{f}_m\right)\right) \qquad (3)$$

where, $\mathbf{C}_b^y$ and $\mathbf{C}_m^y$ are vectors from the saggittal axis (y-axis) to the loading points. The y-axis is set to coincide with the center of gravity of the biting forces. And k is a weighting factor. We provide k = 1000 because the moment around the y-axis should be converged to zero and sum of muscular forces is quite huge compared with the value of the moment.

4.2 Computational results

The finite element model was generated from CT images of a patient whose jaw has a severe deformity using our individual modeling method [1]. Biting forces were measured by a pressure sheet and the higher biting forces were observed at the left side as shown in Figure 5. Table 1 summarizes estimated muscular forces and reaction forces at condyles using equation (2) and (3).

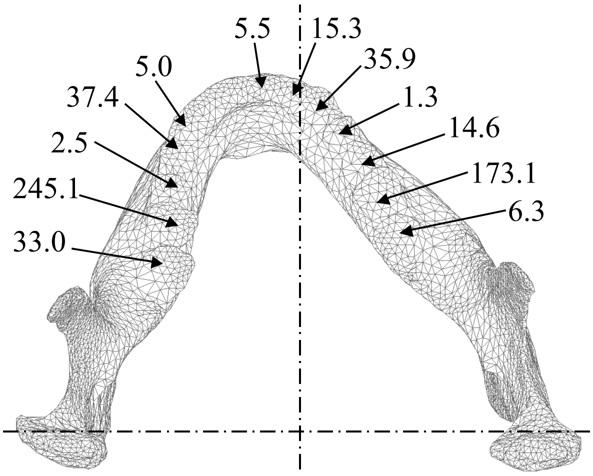


Fig.5 Individual model and biting forces [N]

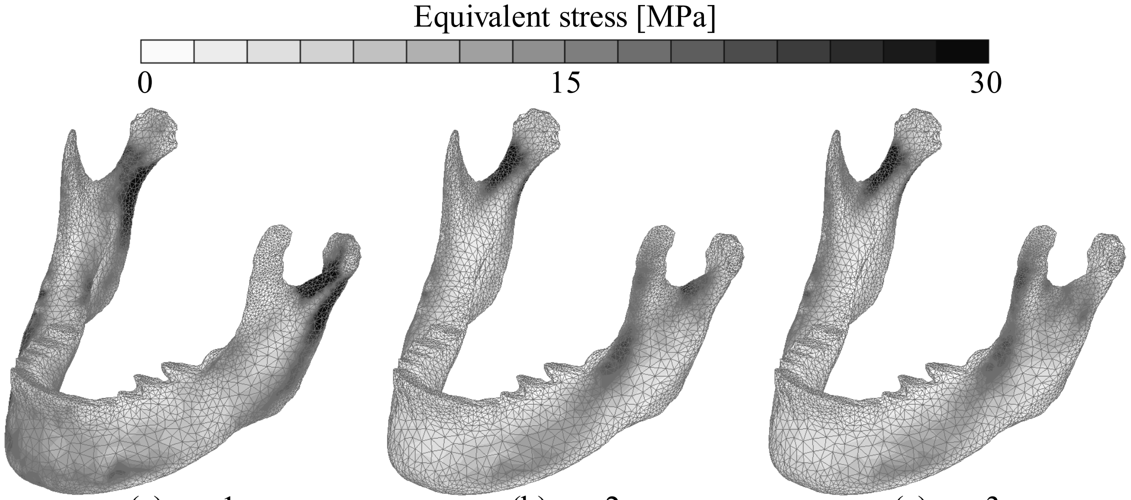
When n is equal to 1, only two muscular forces contribute the biting. This condition seems to be unrealistic since muscles in the living body are considered to be cooperatively working. In case of n = 3, forces of left masseter or anterior temporalis are less than these of right ones. This is not reasonable because muscles at the side where higher biting forces are applied should work harder than those at another side.
We executed stress analyses of the model using the estimated muscular forces. Young's moduli for each element were assigned referring the report by Carter et al. [3]. Figure 6 shows the computational results of equivalent stress distributions. There is no significant difference in the stress distributions between the methods in case of n = 2 and 3, although n = 3 are unreasonable as above mentioned. This similarity may be caused because both mechanical conditions are not so different on the whole.

5. CONCLUSIONS

In this study, we pointed out necessity of development of the support system for setting boundary conditions for effective individual simulations and discussed necessary functions embedded to the system. The developed system facilitated the tasks and shortened the working time. We also examined the estimation method of muscular

Table 1 Estimated muscular forces and calculated reaction forces at condyles

		Muscular forces [N]					
		(a) $n = 1$		(b) $n = 2$		(c) $n = 3$	
		L	R	L	R	L	R
Masseter		0.0	0.0	170.5	141.1	147.1	155.5
Medial Pterygoid		576.0	0.0	181.0	107.0	153.2	138.6
Lateral Pterygoid		0.0	0.0	37.3	8.7	59.5	43.4
Temporalis	Anterior	0.0	319.4	170.0	164.6	147.4	166.1
	Posterior	0.0	0.0	49.5	30.7	83.6	75.4
Sum of muscular forces [N]		576.0	319.4	608.3	452.1	590.8	579.0
Reaction forces at condyles [N]		316.7	242.5	219.4	193.3	161.9	212.1



(a) $n = 1$ (b) $n = 2$ (c) $n = 3$

Fig.6 Comparison of stress distributions in the FE model of a human mandible

forces on the viewpoint of effective setting of boundary conditions. Muscular forces were estimated by three kinds of objective functions and stress distributions were analyzed. The computational results were evaluated and it was found that the method of minimization of square of muscular forces was the most suitable for this study.

Using the optimization method, medical expert will be effectively able to set up conclusive mechanical conditions. The medical expert reviews the estimated results and revises them checking several important muscular areas. This complementary tool will greatly reduce the time to set up the boundary conditions.

6. REFERENCES

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