Patient-Specific Finite Element Modeling of a Human Skull Based on the X-ray CT images

Norio INOU[1], Michihiko KOSEKI[1], Masaya JONISHI[1] and Koutarou MAKI[2]
[1]Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo, Japan
[2]Department of Orthodontics, Showa University, Tokyo, JAPAN

1. INTRODUCTION

Patient-Specific finite element modeling based on multi-sliced images such as CT or MRI data is a powerful method for biomechanical analyses of bones. Several studies have applied to masticatory systems, but almost of them have limited to mandibular bones because human skulls have very intricate structures.

Voxel modeling that represents a bony shape with small cubic elements is often used as one of patient-specific methods [1]. However, it is difficult to apply the method to a human skull directly because a huge number of elements is needed for the modeling.

The authors have proposed an individual modeling method based on X-ray CT data [2]. The method generates a finite element model with tetrahedral elements. Our previous report describes application to a human mandible and shows the validity of the method generating a precise mandibular model with a limited number of elements [3]. In this study, we challenge to apply our method to a human skull.

2. MESHING ALGORITHM

Our modeling method adaptively controls element size according to characters of shape such as curvature and thickness. The method is composed of the following four processes [2].

1) Extracting a voxel space of a bone from multi-sliced CT images.
2) Distributing nodal points in the space.
3) Generating finite elements by use of Delaunay triangulation.
4) Finishing the model by removing excessive elements.

To control finite element size according to shape of a bone, we have introduced a "form factor". The form factor is calculated by the following step 1 and 2. Then the distribution of nodal points is performed by the next step 3.

Step 1: Counting number of subsistent voxels Nv around a remarking point in a cubic inspection region of which side length is n as shown in Fig. 1.

Step 2: Computing a form factor Vs as the following equation.

$$Vs = \left| Nv - C \right| = \left| Nv - \frac{n^3}{2} \right| \qquad (1)$$

Here, C is a criterion measure to compute the form factor, which is set to be half value of the cubic space.

Step 3: Distributing nodal points according to the form factor Vs. Nodal points are sparsely distributed at the portion where Vs is small. On the other hand, they are densely distributed at the portion where Vs is large.

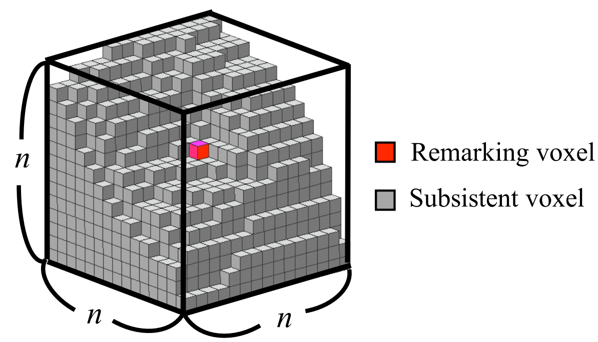


Fig 1. Inspection region of form factor.

3. APPLICATION TO A HUMAN SKULL

It is important to consider proper allocation of finite elements under a limited number of elements. That is, large size of elements should be used to represent intricate portions of a modeling object while small size is for simple ones in shape. First we discuss the inspection region for precise modeling because the inspection region may affect calculation of form factor in application to an intricate object such as a human skull.

We calculated distributions of form factor Vs for a mandible and a skull with two kinds of inspection regions using the multi-sliced images. Figure 2 shows histograms of the form factor when side length of the inspection region n is 13 and 31. The horizontal line denotes the form factor, and the vertical line denotes ratio of voxels of the each bone. In case of the mandible, the distributions of Vs is almost same when n is either 13 or 31. This means that we can obtain same quality of mandibular models for n=13 or 31.

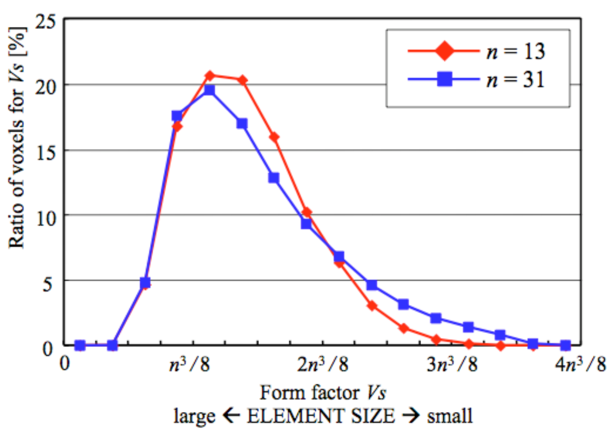
On the contrary, the distributions of Vs are different in case of the skull for n=13 and 31. When n is 13, the distribution has one peak and is similar to the case of the mandible. However, when n is 31, the distribution has two peaks and one of the peaks is located at the larger form factor. This means that a larger number of small size of elements will be produced compared with the condition of n=13. This suggests that the condition of n=31 may fail to calculate proper form factors because the n=31 is too large for the human skull.

Next we performed patient-specific modeling of the human skull. Figure 3 shows results of the patient-specific modeling when n is 13 and 31. The both models are controlled to have an almost same scale. When n is 13, the model is generated with good quality. Large size elements are allocated to simple structural portions of the skull and small size elements to intricate portions.

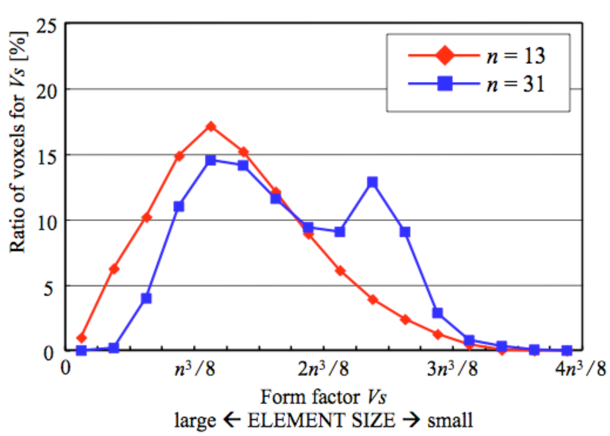
On the contrary, the condition n=31 causes an improper allocation. Many small size elements are used for upper part of the skull although they should be used for intricate structural portions. As the result, elements are insufficient to express the intricate bony portions of the skull.

4. CONCLUTIONS

This paper reported a patient-specific modeling of a human skull with our method. For precise modeling, we examined the proper inspection region that controls element size. We demonstrated that the proposed method generates a precise finite element model of a human skull with a proper inspection region.

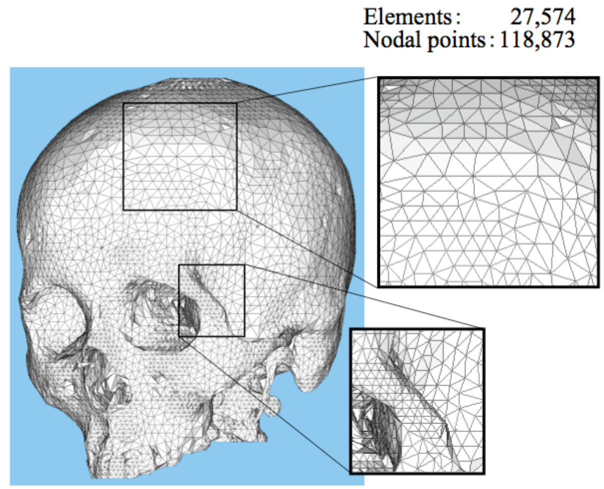


(a) case of a mandible

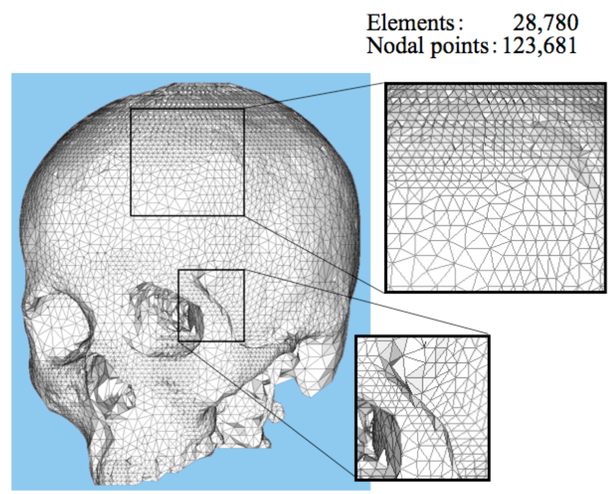


(b) case of a skull

Fig 2. Histograms of the form factor.



(a) side length of inspection region n=13



(b) side length of inspection region n=31

Fig 3. Generated patient-specific finite element models of a human skull with different inspection regions.

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