An Easy and Quick Formulation of Patient-Specific 3D-FEM Dentate Mandible Model with Periodontal Ligament for Mechanical Analysis *

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Abstract
In recent years, the number of patients with mandibular defects is increasing, and the orthognathic surgery of mandible has become a common treatment for re-establishing functional and aesthetic anatomy by repositioning displaced skeletal elements. To decrease a heavy burden and high risk of the surgery falling on the patients and clinicians, the present authors have developed a mechanical support system for orthognathic surgery. An easy, quick and patient-specific mesh generation including the periodontal ligament is essential. First, a mandible template was obtained manually, which requests the small number of elements. It is composed of 7 different materials and could reproduce the original shape of each material pretty well with a reduced number of elements. Next the template of around 6600 nodes is mapped by a simple formula in a moment of time to fit the patient’s mandible polygonal image obtained from an individual CT image. The calculation with the resulted patient-specific mesh by a 3D FEM code is also performed successfully.

Key words: FEM, Patient Specific Model, Mandible, Tooth, Periodontal Ligament

1. Introduction
In recent years, the number of patients with mandibular or maxillary defects is increasing, where the defects include mandibular or maxillary protrusion or retraction, open or cross bites and facial asymmetry. These are due to congenital anatomy and jaw deformity and most of them are disorder in the growth of mandible. One or the combination of following therapies such as orthodontics, implant and surgical orthognathics is performed depending on the type and degree of defects to treat malocclusion, functional disorders such as masticatory disturbance and articulation disorders, cariogenesis, and hang-up. Orthognathic surgery has become a common care to establish normal functional and aesthetic anatomy by repositioning displaced skeletal elements usually together with orthodontics before (for decompensation) and/or after (for stability of reposition and firm occlusion) the surgery. It
is performed in a shorter time and effects of this treatment are astonishing compared to orthodontic therapy alone.

The surgery is performed under a team of oral surgeon, anesthetist and orthodontist after the detailed study with 3D-CT (three-dimensional computed tomography), articulator and facial expression photograph. However, this surgery is carried out for the hard tissue that is connected to another hard tissue through temporomandibular joints and that actively moves and supports large occlusal force firmly both in dynamic and static manners. These need a mechanical study based on the stress and strain distributions predicted by the FEM (finite element method) for an individual patient. The mechanical information such as not only stress and strain distribution but also the transfer of occlusal forces within the gnathic bone and the response of temporomandibular joint is useful to avoid the secondary postoperative complication and to decrease a heavy burden and high risk of the surgery falling on both patients and clinicians.

The patient-specific FEM models have been developed by using directly measured geometrical information such as with CT, diagnostic cast, radiograph and coordinate measuring machine. Most of previous relevant papers convert the 3D-CT image to the polygonal one that is directly used for the mesh generation of a patient-specific FEM model after overcoming problems in several processes, some of which are mentioned in the next section. A boundary constrained Delaunay triangulation procedure can create a FEM mesh with multiple phases such as cortical and spongy bones from the 3D-CT image through the nodal point distribution process and deletion of unnecessary elements produced in the concave region. And the mesh geometry could be optimized for more accurate mechanical information with less computing time and efforts. There is another method that uses a template, which is transferred to fit the polygonal images. However, most of these papers deal with mandible without the pdl (periodontal ligament) that locates between tooth and bone and takes on important roles of both supporting and distributing occlusal loads. The model that is based on other tools could not realize well the practical topology of human mandible, while the pdl is usually included due to its important role for the stress distribution around the interface area between tooth and alveolar bone.

In this paper, the FEM simulation method that is requested in mandible osteotomy is discussed first. Then a method based on the template is developed to include the pdl and to use a new simple transformation method of the template. Finally, the numerical calculation is performed, which verifies that the proposed transformation method is applicable to the thin pdl layer of about 0.2 mm thick.

Though the template is refined to include not only the pdl but also tooth with enamel, dentin and pulp, the number of element is comparatively small. It is noted here that the much more refinement of the mesh will be considered in the future if there is a request from the clinical point of view and that an application to the other patient-specific mandibles is considered to be beyond the scope of the present article, since this paper focuses on the capability of transformation that realizes an acceptable mapped morphology to be calculated by a FEM codes and to yield a reasonable role of the pdl.

At present the capability of the personal computer is increased and a FEM model with about 500,000 elements could be solved without so serious problem if some treatment such as the Delaunay triangulation procedure is applied. However, the present template method is simple and it could be applied to not only the perfect polygonal one but also the one including small artifacts and defects and others such as the voxel one. The present transformation formula also adopts any existing mandible mesh as a template in theory.

2. Requisites for the numerical simulation of mandibular osteotomy by FEM

Realization of pdl (periodontal ligament)

The dentate mandible has eight tissues, that is, enamel, dentin, cement and pulp of the
tooth, alveolar, cortical and spongy bones, and pdl. Both the pulp and pdl are soft tissues and the pdl reduces the stress concentration along the boundary between tooth and alveolar bone whose stress is quite critical for the re-modeling of alveolar bone. Stresses in the pdl may have some effect on its inflammation that may lead to the gingival disease, which is assumed to have some relation to the bone absorption again. Thus, the incorporation of the pdl is a key factor for the analysis of mandible and the absorption of bone and gingival disease can be discussed from the mechanical point of views.

However, most of the previous literature did not include the pdl in the FEM model. It is related to the following problems. The thickness of pdl is quite thin, which leads to quite a few elements to the whole dentate mandible model and the conventional computational machine could not operate well. It is also difficult to pick up the complete topology that has a range of CT indexes of Hounsfield Unit corresponding to the thin pdl since the one pixel is corresponding to 0.4mm that is two times larger than the thickness of the pdl when 512 pixels are used for a scan of 200mm. Of course, there are analyses that include the pdl if a single tooth with surrounding tissues of mandible is concerned as an academic or orthopedic problems\cite{9-13}. The model in Refs.8 and 14 includes the whole dentate mandible with pdl and was formulated manually from a CT, or diagnostic cast and radiograph images of a dry dentate mandible and it rather looks like a humanoid mandible. They used the hexahedral element that realizes stress and strain variation within itself, while auto mesh codes usually yield a tetrahedral element with four nodes, which has constant stress or strain within the element. Thus, the hexahedral element is used to yield refined mechanical behaviors in the present paper.

Conventional FEM models and the present idea

In the conventional FEM modeling with 3D-CT, hundreds of CT images are merged into a three-dimensional voxel image that leads to a three-dimensional polygonal image by using quite a few small triangles. There is also a case that the teeth image is obtained separately and two images are merged into a single image of dentate mandible\cite{15}. The auto mesh code converts them into the FEM mesh geometry. However, cracks and extra surfaces appear in the FEM mesh geometry composed of tetrahedral elements, since the surface triangle is not always complete. The operator must find out where the incomplete surface is out of a large number of triangles and rearrange the mesh geometry manually to be solved by the FEM code. In the Delaunay triangulation procedure, unnecessary tetrahedral elements are formed and must be removed. This might be performed automatically by using the CT indexes in the voxel. Occasionally another surface is adopted to cover the polygon and the surface is meshed to form 3D FEM model\cite{6}, where the surface curvature is used to control the density of nodes to have the efficient calculation.

When a range of CT index corresponding to each tissue is used, a polygonal image of each tissue is obtained and is converted into separate FEM mesh geometries. In this case each mesh of different tissues must be the same at the same position of the boundary, which is treated well in the Delaunay triangulation procedure. When the whole FEM geometry is made first, the assignment of mechanical properties to each element needs each CT indexes again. Since the voxel size is usually larger that the pdl, the operator might have to accept irregular geometries of interfaces.

Though a series of soft-wares used in the process from CT images to the polygonal image are well developed and the process becomes a routine work for a medical technician related to orthopedics and dental surgery\cite{15}, it is not still the same to obtain the FEM mesh geometry from the polygonal image. The present situation is not acceptable for the parametric study before each surgical operation.

A FEM model is formulated first. The model must be appropriate to be a template. Then, a mapping is contrived for a quick and easy realization of a patient-specific model.
3. The present FEM method for dentate mandible with pdl

Manual formulation of dentate mandible FEM model with pdl

Since the FEM template model must have characteristics of the natural dentate mandible and the incorporation of the pdl is desirable, a FEM mesh is constructed manually this time, which requests the small number of elements and thus the hexagonal element that has linear strain distribution within each element. Conventional manual formulation\(^8\), \(^14\) could not realize the characteristics of a dentate mandible with teeth including the inside structure. Therefore, the representative points and their coordinates are picked up directly from a polygonal image obtained from 3D-CT image of a patient. Though the whole polygonal image of mandible is obtained, only the right half is shown in Fig.1 since only this half mesh geometry is made manually. Here, major artifacts and defects outside of the mandible with teeth are removed and those inside are still left. This is enough for the present purpose.

The process to obtain the polygonal image of the dentate mandible is not described in this paper. It was presented in detail in Ref.(\(^15\)) including that a three-dimensional laser digitizer was used to obtain the dental surface image of crowns, since the CT image of crowns is disturbed by the metal artifact of prosthetics and orthodontic appliance and that a new and reliable method to match roots, crown and mandible was also developed. The process to obtain the FEM geometry from the polygonal image is as follows.

First the region of each tissue is defined. Three polygonal images of spongy and cortical bones and teeth are used. The one of spongy bone becomes the boundary between cortical and sponge bones. The pulp is represented as the inner surface of a tooth. It is mentioned here that its stiffness is set zero since there is no node inside the pulp region, that is, no possibility of the zero determinant of the whole stiffness matrix. The enamel is defined as the surface layer of the crown and most of the thickness is set as around 1mm. Remaining part of the tooth is defined as the dentin here, though the surface area of the root is called as cement that has different microscopic structure from dentin but has almost the same mechanical properties. The pdl is defined as the thin layer of around 0.25mm between cement and alveolar bone, whose thickness and material constants are defined as about 1mm and similar to those of the cortical bone, respectively. Totally seven components are defined.

Next the mesh geometry is generated. Basically the hexagonal solid element is used as mentioned above. Sometimes its contraction of the pentahedral or tetrahedral solid element is used near the neck and apex of root. To prepare for the future modification or application to the implant, the mesh geometry is subdivided into longitudinal blocks as shown later in Fig.5. The side surface of cortical bone in each block is set to have the same topology of elements. The inside of cortical bone is occupied by the spongy bone that also has the same topology as the side surface. The mesh of each tooth is set to have the same topology except a little modification of roots of molar. The present 1\(^{st}\) and 2\(^{nd}\) molars have two and almost one root, respectively. There is a case of three roots, too. It is necessary to prepare three kinds of mesh for each molar to apply this template to various patients. The pdl and related alveolar bone are set to have almost the same mesh geometry to the root surface one.

It should be mentioned again that only the half mandible template is constructed.
manually from the polygonal image of Fig.1. The left half template is obtained as a mirror image of the right half and it is understood that the whole mandible template has characteristics of the natural mandible including the pdl. In this paper coordinates of $x$, $z$ and $y$ are defined as the direction normal to the median plane, longitudinal direction, and direction normal to both $x$ and $z$, respectively.

An easy and quick formulation of an individual patient’s FEM dentate mandible with pdl: a mapping method

The template must be transformed to have the almost same geometry to the polygonal image of a patient. It is not necessary to transform the right half since it is formulated from the right half of the polygonal image of the patient. The transformation is performed by the mapping formula. This mapping must be simple, since around 3300 nodes, that is, around 10,000 coordinates this time or 20,000 ones in case of the whole template have to be treated.

The equation for the linear interpolation of the one-dimensional space is represented by

$$x = x_1(d_2 / (d_1 + d_2)) + x_2(d_1 / (d_1 + d_2)), \quad (1)$$

where $x$, $x_1$, $x_2$, $d_1$ and $d_2$ denote values of displacement at a point $p$ and reference points $p_1$ and $p_2$, and distances between points $p_1$ and $p$ and points $p$ and $p_2$, respectively. Equation (1) is rewritten as

$$x = (x_1/d_1+ x_2 /d_2 ) / ( 1/d_1+1/d_2 ), \quad (2)$$

which means that the inverse of distance becomes the weight to the referenced variable. Now Eq.(2) is expanded to three-dimensional space with $N$ reference points shown in Fig.2 as follows,

$$z = \Sigma( z_i(d_i)/\Sigma( 1/d_j )). \quad (3)$$

Here, $z$, $z_i$, $d_{ij}$ and $\Sigma$ denote three dimensional vectors of displacement of the mapped point and reference point $i$, the distance between mapped point $p$ and reference point $p_i$, and the summation from 1 to $N$, respectively.

Transformed coordinates of reference points of the FEM mandible template are the same to those of the polygonal image of the patient. Reference points shown in Fig.2 are set as follows: one point of each of vestibular, lingual, mesial, distal and occlusal surfaces and at apex of root, that is six points in incisor, canine and premolar and seven points in molar of the present example; one point beneath each root and at the base of mandible; three points in the ramus of mandible such as two at the top edge and one at the base of mandible; four and two points in coronoid process and angle of mandible, respectively; six points in condylar process and one between condylar process and angle of mandible along the inclined lower edge. The number of reference points is 69 for the left half part.

Preliminary results showed that Eq.(3) was not enough to have an acceptable displacement. Thus several improvements are taken account to improve the mapping formula. The resulted formula is

$$z = \Sigma( a_{ij}(d_i^b)/\Sigma( a_i/d_i^b ) ), \quad (4)$$

where $a_{ij}$ and $b$ denote constants. The constant $a$ adjusts distribution density of reference points in each block. The constant $b$ controls the effect of $d_{ij}$. Those constants have no relation to each other theoretically, since $a$ and $b$ are related to the number of reference point in each block in Fig.5 and the distance between reference and mapped points, respectively. The details are explained in the next section.
4. Results

FEM dentate mandible template: the right half obtained manually from the patient’s polygonal image and the left one as a mirror image

The mesh of each tooth has three, four and five elements along labiolingual, mesiodistal and longitudinal directions, respectively as shown in Fig.3(A). A small space is set between teeth and the contact analysis is not considered in the present calculation under loading. Crowns occupy two columns and their surface is enamel. The pulp and pdl are shown in Figs.3(B) and 3(C), respectively. The cortical bone related to each block of the alveolar part has four elements along both mesiodistal and vertical directions as shown in Figs.3(D) and 3(E). Additional four elements on the top of both vestibular and lingual sides are bent toward the neck of tooth and three more between crowns on the top are too. There are three by four elements at the bottom. The cortical bone at ramus of mandible has three by four elements on each side and three elements at both the top and bottom of the cross section, while the spongy bone has three by four elements. The number of element in the spongy bone is increased near the neck and apex of root. The inside structure is disclosed in Fig.3(E), where surface layers are detached deeper from the bottom to top and from the first molar to the first premolar. The number of points which are picked up and set as nodes is 3328 and 2683 elements are made manually and the total numbers of template nodes and elements are 6622 and 5366, respectively.

As was explained in detail each block is set to have almost the same topology and labiobuccal planes between teeth and also between the second molar and ramus of mandible. Thus, each block is replaced by another one. For example, if a second molar with
two separate roots is necessary, a slightly modified present first molar block is usable. This template can be applied to the simulation of the implant behavior if one block is replaced by the one with an implant.

**Individual patient’s FEM mandible by mapping of the template**

The larger constant $b$ increases and decreases the effect of near and far reference points, respectively. The result of Eq.(3), where the summation was taken for the all 69 reference points, showed that the mapping was degraded by the effect of far reference points. Equation (1) or (2) represents the linear change of value as the function of distance, which is usually accepted as the first order approximation. However, when the number of referenced point is more than 2, Eq.(3) increases the effect of far reference points too much. If there are reference point 1 at left with distance and displacement of 1 and 9, respectively, and 7 others at right with distance from 2 to 5 by 1 with the same displacement of 0, the plausible result of displacement is 6. However, Eq.(3) yields $9/(1+1/2+1/3+1/4+1/5) = 3.9$, which is due to the effect of far points.

Figure 4(A) shows the polygonal, mapped and template images from left to right. This poorly mapped image is obtained by Eq.(3). The displacement marked by a white arrow of the mapped condylar processes is not enough. Though the right side in blue and brown is under the right side in pink and blue, respectively, the corresponding edge lines indicate the insufficient mapping of this case. It is also noted that the mapped shape of coronoid process is a little strange and is not similar to the polygonal image in brown. Figure 4(B) is obtained by Eq.(4) together with several additional conditions that are explained later. Mapped image in green almost corresponds to the polygonal image in Fig.4(A) and the resulted displacement is shown by a white arrow that is several times larger than the case of Eq.(3). The successful mapping of coronoid process is highlighted in yellow. It is concluded that this mapping is acceptable compared to the case of Fig.4(B).

Thus, it is necessary to nullify the effect of far reference points by setting the constant $b$ as 2, since the constant $b$ of 1 can not realize the block shape well and $b$ of 3 confines the effect of reference point at the too localized area near the reference point. However, the introduction of exponential $b$ is not enough and the mandible is divided into ten blocks as shown in Fig.5 and the summation is performed within the affiliated block and its neighboring ones.

![Fig.5 A FEM mandible template](image)

![Fig.4 Mapped coronoid and condylar processes based on (A) Eq.3 and (B) Eq.4 with additional conditions](image)
as shown in Fig.6 for the case of block 6.

The effect of each block should be the same, that is, the same number of reference points is required. This is realized by the constant of $a_i$ such that it is set as $7/3$ in the block 8 of the ramus of mandible where three reference points are picked up as is observed in Fig.2. Other $a_i$s of 1, 7/9, and 7/6 are set to blocks 1 to 5 and 10, blocks 6 to 7, and block 9, respectively.

The results are shown in Figs.7, while the enlarged one of Fig.7(B) was already shown in Fig.4(B). Both polygonal and template, both template and mapped, and both polygonal and mapped images are presented in Figs.7(A), (B) and (C), respectively. The blue polygonal image in Fig.7(C) is the same to the brown one in Fig.7(A). The same color of brown is not used in Fig.7(C) to avoid the confusion between the polygonal image and mapped teeth image (in burnt ocher in Fig.7(C)). Figure 7(C) shows that the mapped FEM dentate mandible and polygonal surfaces occupy almost the same position.

Here, no formula with critical numerical values is used to assess the mapping performance. Minor artifacts and defects left on the present polygon cause some problems for assessing the performance of mapping, since the basic parameter of performance is assumed to be the radius of a sphere that contacts with the nearest quadrilateral template patch and has its center at each node of a polygon with some defects. The future assessment will firstly request a smoothing process to a polygon before formulating a template.

The present assessment is based on three points, two of which were mentioned in relation to Fig.4. They are necessary and sufficient overall displacement, no local deformation and one more, that is, the same kind of alternation of outer surface between template and polygon. The third means that the difference between the polygon and mapped template is the same to the one of the polygon and manually formulated template, while the latter difference is considered as the minimum one within the scope of the present formulation.

It is summarized that the present paper proposes a mapping method of Eq.(4) together with (1) constant $b$ of 2 to increase the effect of neighboring reference points, (2) constants $a_i$s to adjust the number of reference point in each block and (3) the summation within the affiliated block and its neighboring ones. The process for picking up coordinates and mapping requires less than
one hour.

5. Numerical solution

A numerical calculation is performed by using the mapped FEM geometry, that is, the individual patient mandible model. Two heads of mandible are fixed in three dimensions, the biting force is resulted from the fixed displacement condition along the longitudinal z direction with free conditions to other two directions at the central area of occlusal surface, and seven kinds of muscular forces shown in Table 1 are applied. Weight and scaling factors in Ref.(14) and the information of loaded nodes and load vectors for muscles in Ref.(16) are used. Though nodes and vectors are presented only for the left side, the masticatory muscle forces are applied also to the right side at the nodes in symmetry with respect to the median plane. However, the magnitude of load that is obtained as the product of weight, scaling factor and directional vector, is different from the left side one since different scaling factors are used. Material constants of Young’s modulus E, Poisson’s ratio ν and shear modulus G in Table 2 are almost the same to those in Ref.(14). Isotropic and orthotropic mechanical properties are assigned to tooth and mandible, respectively. Resulted stress distributions are shown in Fig.8 and Fig.9 for the biting force on the right first molar and canine, respectively.

Since heads of mandible and a tooth are fixed in three and one dimension, respectively, and tensile muscle forces are applied between heads and alveolar part, the mandible responds like a curved beam, which yields tensile and compressive beam stresses at the position away from the fixed points. However, the beam stress is interrupted by alveoli and complicated stress distribution is expected especially near the loaded tooth. Figure 8 shows the equivalent stress of the whole mandible, the amplified one at the inclined and curved section and the one of pdl. The high stress between heads and alveolar part in Fig.8(A) is due to the bending deformation by tensile muscle forces applied to these zones. The loaded tooth also shows high stress. The effect of the pdl is shown in Fig.8(B), where only two roots of the loaded 1st molar have high stress and other roots have practically no stress. The soft pdl shields load-free teeth against environmental stresses. The stress decreases along the mesial direction from the 1st molar and does not decrease so well along the distal direction since the muscle force is applied there. Figure 8(C) shows the stress distribution

Table 1. Loading condition of masticatory muscles14),16)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Weight (N)</th>
<th>Scaling factors</th>
<th>No of nodes-L*</th>
<th>Unit vector coordinates-L*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Superficial masseter</td>
<td>190.4</td>
<td>0.72</td>
<td>0.6</td>
<td>14</td>
</tr>
<tr>
<td>Deep masseter</td>
<td>81.6</td>
<td>0.72</td>
<td>0.6</td>
<td>6</td>
</tr>
<tr>
<td>Medial pterygoid</td>
<td>174.8</td>
<td>0.84</td>
<td>0.6</td>
<td>9</td>
</tr>
<tr>
<td>Anterior temporals</td>
<td>158</td>
<td>0.73</td>
<td>0.58</td>
<td>20</td>
</tr>
<tr>
<td>Middle temporals</td>
<td>95.6</td>
<td>0.66</td>
<td>0.67</td>
<td>3</td>
</tr>
<tr>
<td>Posterior temporals</td>
<td>75.6</td>
<td>0.59</td>
<td>0.39</td>
<td>3</td>
</tr>
<tr>
<td>Inferior lateral pterygoid</td>
<td>66.9</td>
<td>0.30</td>
<td>0.65</td>
<td>4</td>
</tr>
</tbody>
</table>

* L denotes left and the right side value is the same in number and in symmetry with respect to xz-plane for coordinates.

Table 2. Isotropic tooth and orthotropic mandible material properties14)

<table>
<thead>
<tr>
<th>Material</th>
<th>Ex (MPa)</th>
<th>Ey (MPa)</th>
<th>Ez (MPa)</th>
<th>Vxy</th>
<th>Vyz</th>
<th>Vzx</th>
<th>Gxy(MPa)</th>
<th>Gyz(MPa)</th>
<th>Gzx(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>80,000</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dentin</td>
<td>17,600</td>
<td>-</td>
<td>-</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pdl</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
<td>0.45</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cortical(AIveolar) b.</td>
<td>17,000</td>
<td>6,900</td>
<td>8,200</td>
<td>0.31</td>
<td>0.325</td>
<td>0.315</td>
<td>2,800</td>
<td>2,900</td>
<td>4,600</td>
</tr>
<tr>
<td>Spongy b.</td>
<td>960</td>
<td>320</td>
<td>390</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>90</td>
<td>130</td>
<td>170</td>
</tr>
</tbody>
</table>
and there is practically no stress at the inside surface of the pdl except the one of the 1st molar. Stress distribution is noted in the outer surface especially loaded tooth and its neighbor region and the region near the muscle load, which corresponds to the left posterior. Figure 9(A) shows the normal stress $\sigma_{zz}$ distribution. There is compressive stress distribution inside and high stress is observed near the central tooth neck of canine and at the bottom as expected. There is small tensile zone at outer surface near the neck, which is a reasonable one to resist the compressive displacement there. There is also a small tensile region inside, whose surface is parallel to the loaded z direction and thus is not the main compressively loaded region. Since the Poisson’s ratio of pdl is 0.45 and the pdl is sandwiched by extremely hard tissues compared to itself, the strong interaction between normal components is expected, which can result in tensile stress. The normal stress at the inside of both the 2nd incisor and 1st premolar cases is practically zero, while there is some outside. These are related to both the local loading and bending deformation mentioned for Fig.8. Figure 9(B) shows the shear stress $\sigma_{yz}$ distribution. The right side is the pdl of canine. It is positive at the upper side and high near the tooth neck and is negative at its counter side, which is reasonable. There is practically no shear stress inside of the pdl related to the 1st molar.

Calculated stress distributions in the pdl are reasonable and the mechanical explanation is
roughly possible. This may be due to the hexagonal mesh that realizes the linear stress distribution. Dental and extensive discussions on numerical results after the application of this mapping method are performed in Ref.(16).

6. Discussions

Though only the half of FEM template is mapped, the present method could be applied to the whole geometry. It claims that the present mapping is a simple and easy method to obtain the patient-specific FEM mesh geometry including the pdl from his/her polygonal image of dentate mandible. When any individual patient’s mandible image and an established FEM model are available, the present mapping method could be applied to them as the reference and template model, respectively.

If the basic response related to the pdl in the mandible or maxilla is focused, a FEM model with the large number of elements by the conventional method is appropriate. However, the parametric study for each patient before the operation needs a simple and quick process for the whole analysis. This simple mapping transformation might be appropriate.

7. Conclusion

1. A FEM dentate mandible template with the pdl is formulated manually. It keeps characteristics of the natural mandible such as the number of tissues and their geometry.

2. A mapping equation to realize a quick and easy formulation of an individual patient’s FEM model for dentate mandible including the pdl is proposed together with three conditions: one constant to increase the effect of neighboring reference points, another constant to adjust the number of reference points, and the summation range to exclude far reference points.

3. A realistic individual patient’s FEM mandible mesh geometry divided into 7 materials is obtained quickly and easily by using 69 reference points for the half model. The full mesh geometry has 6622 nodes and 5366 elements.

4. A numerical calculation is performed by using the mapped FEM geometry, that is, the individual patient mandible model and the reasonable stress distribution in the pdl and its role in stress transfer are observed.

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