A METHODOLOGY FOR GENERATING THE FINITE ELEMENT MESH OF A TYPICAL HUMAN TOOTH

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Abstract. *Finite element techniques have gained, in the last decade, increasing attention by the health-related professionals, and in particular by the dentistry community. The use of finite element modeling for prediction of temperature distribution, adhesive cohesion, and stress-strain behavior of human teeth and implants is undoubtedly one of the most promising fields of research in dentistry, and also an important field for the finite element professional. In order to generate a finite element mesh it is necessary to obtain an accurate description of the geometrical properties of a solid specimen, which should include even the physical properties of each constitutive material. Since teeth have a quite irregular shape and are composed of different constitutive materials, it was necessary to develop a methodology for automatically (or semi-automatically) generating these geometrical descriptions. Radiology, tomography, and destructive testing (by progressive wear) were implemented and the best results were achieved with the destructive technique. The attempted techniques are reviewed and the resulting geometrical models are shown. These results confirm the importance of accurate modeling on the quality of the finite element results.*

Keywords: *dentistry, finite element method, destructive testing, mesh generation, computer graphics.*

1. Introduction

Amid technological development, dentistry also accompanies this progress. Several of the clinical procedures that were previously empirically adopted nowadays have scientific basis, thus contributing for a better formation of the area professionals (Silver-Thorn and Joyce, 1999; Yaman et. al., 1998; DeVocht et. al., 1996).

Biological phenomena can be studied with the aid of the laws of physics as a result of the advances in computing, by numerical methods, which simulate quite accurately the behavior of the variables involved in these phenomena.

The study of physical forces on teeth has been done for quite some time in order to support the study of the materials employed in dental prosthetics as well for the determination of how to best employ each material.

Among the numerical methods used to simulate mechanical behavior the Finite Element Method is singled out for its user friendliness when solving partial differential equations.

The objective of this work was to contribute for the construction of a Database with shapes and structures of human teeth, stored in such a way that they will be available for future usage in computational simulations, confronting data clinically obtained which require deeper scientific investigation. It is also developed in this work a methodology for the construction of this database, in a step by step fashion, so that it can be reproduced. This would facilitate the validation of this methodology as well as help improve the database.

2. Methodology

The FEM can be used to simulate the physical properties and the response of a solid structure subject to forces by solving the partial differential equation involved in such phenomenon. For its application the method requires a computer to establish the computational model which accurately represents the mathematical problem we are trying to simulate. The main concept involved is the subdivision of the solid body (or structure) in elements of finite (as opposed to infinitesimal) size.

The physical properties are established for each element, and the applied forces can be represented by equivalent forces, applied only at specific points of each element called nodes. These points can be positioned in a three-dimensional Euclidean space, with coordinates X, Y, and Z. The representation of the equivalent nodal forces and of the internal properties by the behavior on the nodes allows the continuous problem within the element to be solved as a system of equations. Thus, it is possible to represent an element only by its nodal behavior. Obviously, there is an approximation involved in this representation, since a few nodes might not represent the actual behavior of the solid portion of the body included in the element. This error is assumed to be small and is minimized by the adoption of smaller elements (refinement) to represent smaller portions of the body. When we take into consideration that the structure is formed by the whole set of elements and that the same node can belong to more that one element, we can superpose all the systems of equations for each element to form a larger system of equations which represent the behavior of the whole structure.

For the creation of this structure, or, more adequately, the computer representation of the solid body (in our case, a tooth) under study, it is necessary to define without question each element. This definition includes the physical properties and the geometric location of all nodes. Two methods were tried for this definition: manual point definition and point definition by real image analysis.

2.1 Manual point definition

The manual definition of the points was attempted as a first approximation of the properties of a typical tooth (Menandro et al., 2001). Utilizing mean measures of teeth (Picosse, 1971), these were drawn in engineering paper, in different views to account for the three Cartesian axes (x, y, z). In this drawing, vertical and horizontal lines were taken, and the crossings were later transferred to the computer. In this way, the teeth were three-dimensionally drawn in the computer, allowing the reconstruction of the coordinate mesh of each point (Menandro et al., 2002).

2.2 Point definition by real image analysis

In this type of definition images of transversal cuts of teeth are analyzed, where, in each cut the outline and the limits of its different internal regions (Orban, 1989). Essential points are also determined, as in the previous method, and the tooth is reconstructed in the computer utilizing the concept of iso-lines, The images are then superposed generating the geometric model.

Different procedures were attempted to obtain the images, but not all of the attempts were successful. Among the non-destructive procedures attempted the most important were X-ray scanning (radiography) and Computerize tomography. Since problems arose for the non-destructive retrieval of the needed images, two destructive solutions were implemented, and one of them is shown in this paper. The destructive procedures involve the inclusion of the tooth in acrylic resin medium and slicing or wear of the specimen.

The first method attempted was by means of radiography. Each tooth would be X-ray scanned, furnishing a real size image of the tooth. This image would be projected on engineering paper so that the teeth structures were identified and transferred to paper. The drawing would be obtained on a scale proportional to the X-ray negative. After the drawings were obtained, the complete procedure as in section 2.1 would be carried out.

Computerized Tomography was also attempted. Similar to the X-ray scanning, this equipment furnishes images on different plane cuts of the tooth. The image obtained present planes distant from each other of five millimeters (or other distance pre-determined in the equipment). The tomography images would be scanned into the computer and the internal constitutive tissues of the tooth would be delimited in the computer. Later, thee tooth would be reconstructed by the superposition of the images, constructing the database.

The next process consists in include the tooth in a medium for support and fixation, allowing for its gradual abrasive wear or slicing. Two graphite leads with 0.5 mm of diameter are also included with the tooth to serve as orientation for posterior repositioning of the images. After construction of the specimen (tooth and graphite leads included in self-polymerizing acrylic resin denture base material) this would be partitioned in 5 mm thick slices, furnishing the images of the surface of each slice for posterior reconstruction of the tooth, in the computer. The surfaces of the slices would be polished and photographed. In the computer, then, the tooth structures would be identified and delimited, allowing for each image to be superposed to the others reconstructing, thus, the tooth.

An alternative process of imaging after the inclusion as described in the previous process is to obtain the images from a worn specimen. After the construction of the specimen (tooth and graphite leads included in self-polymerizing acrylic resin denture base material) this would be gradually worn in a model trimmer, photographing the worn surface (polished). The wear depth would vary from 1.5 to 0.5 mm, according to the anatomy of the specific tooth, in order to represent more accurately the details. After obtaining the images, the internal structures (tissues) of the teeth would be identified and delimited in the computer, allowing for the wear images to be superposed one by one, thereby reconstructing the tooth in the computer.

3. Results

In previous work (Menandro et al., 2002), the authors have obtained accurate results using teeth meshes generated by direct drawing. This proved to be accurate for generic studies, but highlighted a few flaws of the direct drawing process. The details particular to one tooth were smeared in a generic tooth drawing, and the internal tissues (structures) of the tooth, such as dentin, enamel, cemento, etc., might not be in accordance to an actual tooth studied. Direct drawing also showed itself to be quite cumbersome and time consuming, not to mention prone to human errors. New procedures to automatically generate the three-dimensional model of the tooth were necessary. This was the motivation for the present research.

The image collection using dental radiography was attempted without much success, since the internal structures superposed on the dental x-ray film.

It was then attempted the acquisition of the images through Computerized Tomography Scanning (Dentascan), to correctly define the geometric shape of each tooth (Central Incisives, Superior Canines, and also 2nd Pre-Molars and 2nd Superior Molars), as well as their internal constitutive tissues. The tomography procedure, however, was not able to distinctly define the boundaries between dentin and enamel. It is possible to improve the CT definition by adjusting the resonance levels of the CT scanner, but we did not have access to the definitions of the medical equipment. We had, thus, to resort to other methods of geometric definition of the studied specimens. The viable procedure was the destructive testing.

Finally, a process of inclusion and wear of the teeth, though destructive, was successfully implemented. This process consists in teeth selection; inclusion of the teeth; specimen preparation; specimen wear, photography and image storage; definition of the boundaries and limits of the dental structures; and finite element mesh generation.

3.1 Teeth Selection

Since natural teeth were needed, a request was made by the University (Universidade Federal do Espírito Santo - UFES), to Vitória City Hall (Prefeitura Municipal de Vitória - PMV), (Processo 2252270/2000), for the liberation of teeth from the Maruípe Cemetery, as a donation.

After approval, the 400 teeth requested were randomly selected by the cemetery and delivered to the University. After identification of each tooth, only the inferior central incisives, superior canines, 2nd inferior pre-molars, and 2nd inferior molars were deemed of interest for the research. The total group is shown in Table 1.

Table 1. Groups of teeth studied

Group 1	15	Inferior Central Incisives
Group 2	20	Superior Canines
Group 3	20	Inferior 2nd Pre-molars
Group 4	10	Inferior 2nd Molars

Once the teeth were obtained, one from each group was (visually) selected, taking into account its structural integrity and the average measures (Picosse, 1971) in each group.

3.2 Inclusion

The following material and equipment were utilized for the tooth inclusion:

Square base prism;

Silicone Reforplás Mod. RP - 315;

Square base;

Parallel rule Bio Art Mod. 1000;

Superbonder® adhesive;

Graphite leads;

Classic colorless powder and liquid self-polymerizing acrylic resin denture base material; and

Isolating medium for acrylic resin denture base material Vipi Ltda. Type Ceolac.

Before actually including the teeth, some materials were tested so that they could serve as guides for positioning the wear images, as will be described further. Were tested graphite 0.5 mm leads, copper wires, tin wires, aluminum wires and orthodontic steel wire, and gutta-perch. The metallic materials presented overheating problems, causing deformation and creating irregular boundaries. Gutta-perch also was not successful for reacting with the acrylic resin and presenting an irregular boundary as a result. Finally, the graphite 0.5 mm leads were chosen as the material with best behavior, presenting regular boundaries, besides the color contrast with respect to the resin.

Starting the process of inclusion, the square base prism was molded with silicone. On the square base, which has the same measure as the base of the prism, an isolating layer for the acrylic resin was applied. After that, the tooth was fixed with its long axis as perpendicular to the base as possible, using superbonder® for fixation. With the parallel rule, two graphite 0.5 mm leads were fixed to the base taking care that they should be both perpendicular to the base and parallel to each other. After to tooth and the leads are firm in position, the silicone mold was adjusted to the base. The mold is open both on the lower side (base fit) and on the upper side (place were the resin will be poured). After fitting the mold on the base with the tooth and the leads already in place the inclusion process is started, using the technique of Liquid saturation, which consists in adding a little bit of resin liquid and then, in sequence, saturate it with the resin powder. This process was repeated until the tooth and graphite leads were completely covered by the resin.

3.3 Specimen preparation and photography

In the Model Trimmer (Kohlban S. A Model Km 43N) the lateral surfaces of the prism were regularized, making each opposite sides parallel to each other. This is necessary to obtain an angle of 90^o between the base and the lateral sides of the prism. This was verified by measuring the distance between the opposite sides with a digital caliper rule (Stonett Model 727-6/150).

To regularize the specimen base, the specimen was placed on the guiding table of the model trimmer. Laterally it was forced on another guiding ruler, specially made and attached to the model trimmer table to keep a 90^o angle (or approximately) with the surface of the sander disc (Number C2 T 13). The base was worn until it became plane and without irregularities on its surface, acquiring an angle very close to 90^o with the lateral surfaces of the specimen (square base prism).

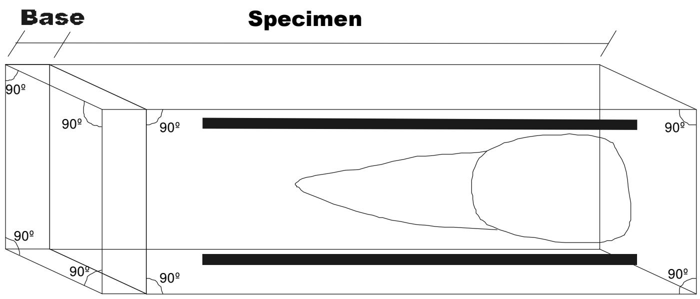

Figure 1. Prepared specimen.

This way it was managed to obtain parallelism between the two bases of the specimen, important for the wear process and for the photography of the worn surfaces, to be detailed later.

Before the specimen is worn, its height was measured with a caliper rule in two points established as reference so that all other measures should be made at the same place, thus increasing accuracy.

As soon as each step of the wearing process was taken, the worn surfaces were polished with sandpaper (Norton #400), checking how much was worn and if it remained parallel to the base, such that parallelism between the worn surfaces was maintained. Everything being checked, the worn surfaces were photographed with a digital camera (Sony Corporation Still Camera Model MVC – FD97 Resolution 2.1 Mega-pixels, Serial number 16701, Japan, Lens Sony/Optical 10X f= 6.0-60.0mm 1:2.8 Ø 52), with a resolution of 1600 x 1200 dpi, recording an image on a 3.5“ disk. The camera was fixed to a static base, with two photoflood bulbs 250w each. A level was used to assure the camera lens is kept perpendicular to the static base, were the specimen lays. This way image focus is best, since it is also assured that the worn surface is parallel to the base.

After the image is photographed it is transferred to a computer where it is checked and stored when deemed satisfactory (visual control). This process of wear/photography/storage is repeated for all wear surfaces, generating an average of 40 surfaces for each tooth. If the image was deemed unsatisfactory the photography was repeated, adjusting the focal distance and the amount of light.

3.4 Defining contour and limit of dental structures

With all the images ready, the identification of the dental structures for each image distinguishing between enamel and dentin, and this from the pulp cavity. This whole process was made using the Corel Draw 9 Software, in which it is possible to amplify the images to the maximum value allowed by the picture resolution, increasing the reliability for this process.

Once the images were digitized the process of geometric model generation was started, following the steps ahead: image vectoring; scale, position and rotation corrections; and image superposition (Sullivan et. al. 2000).

With the image regions well defined the process of vectoring of the images was done. For this the AutoCAD 2000 software was utilized, for its better portability and compatibility with respect to other engineering software.

The boundaries were drawn using splines, smooth curves defined by a series of points, drawn as nurbs (non-uniform rational B-splines), giving thus a better representation to the drawing (Frinkelstein 2000).

The number of points for each kind of boundary (external, dentin, and cavity) was determined by the number of points needed for an accurate representation of the most complex boundary. The other boundaries used the same amount of points and were drawn with the same number of splines.

The splines used are closed splines.

Since the images were not in the same scale and position on the Euclidean plane, adjusts were necessary. Taking the graphite lead points as a basis of reference, a 'mask' was made that covered these points. By transferring this 'mask' to other images and performing the necessary adjusts in scale and rotation were taken. This 'mask' is shown in figure 2.

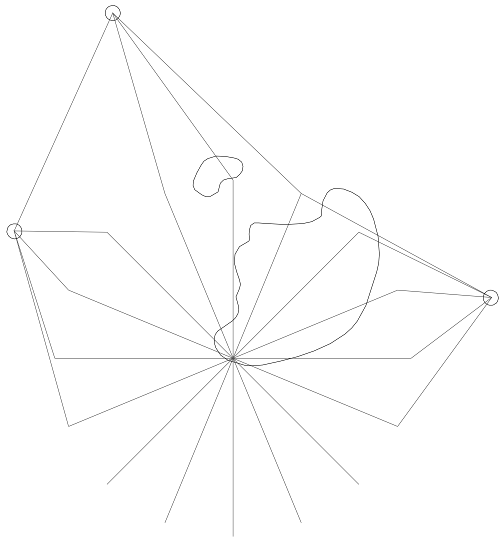

Figure 2. Number 05 cut of the Pre-Molar and reference guides.

After suffering the necessary adjusts, the images were superposed in a single drawing. The cuts were inserted one by one obeying the distance previously measured in the specimen wear process and, at the same time, also obeying the guide 'mask' mentioned above.

After all the 'cuts' were superposed follows the process of connection between them, filling out the lateral lines also using splines, connecting each point on one surface to the corresponding point on the next surface and adding an intermediary point to better mold the splines.

3.5 Finite element mesh generation

Once the geometric model was established, the finite element model can be generated following these steps: generation of the surfaces and solids; and generation of the finite element analysis model, or mesh.

The surfaces were generated in AutoCAD utilizing RULESURF with the system variable SURFTAB1 with 64-segment complexity for external walls and 32 for the internal channel. The horizontal surfaces (between layers) were generated with the same procedure and complexity, adopting a central reference point.

The solids were generated by their limiting of closed surfaces, and the internal structures were generated by Boolean compositions, unions, and subtractions, that is, each solid which represents a 'slice' of the tooth is superposed and united.

The mold for internal structures is made by Boolean subtraction between solids as shown in figure 3.

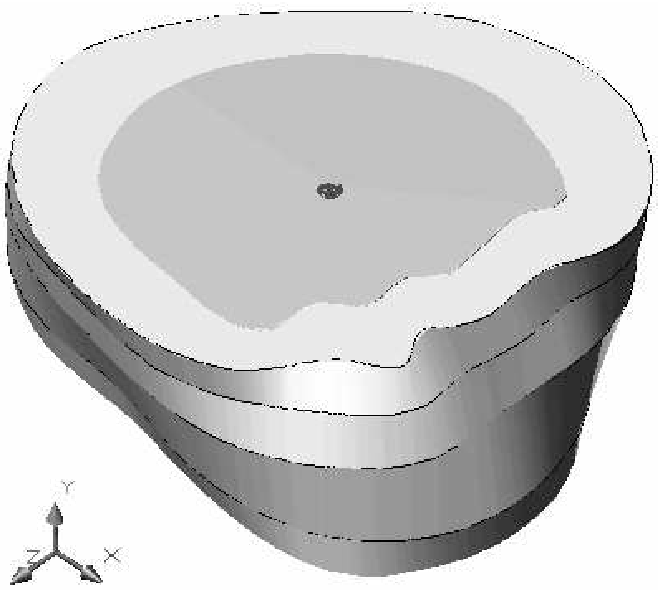

Figure 3. Slices of the canine tooth with the internal structures highlighted.

With the aid of translating software the geometric model can be exported for analysis by finite element software. The geometric model was translated from the AutoCAD (DWG) format into IGES (Initial Graphics Exchange Specification) format, which is a standard representation for exchange of graphic information between CAD/CAM systems.

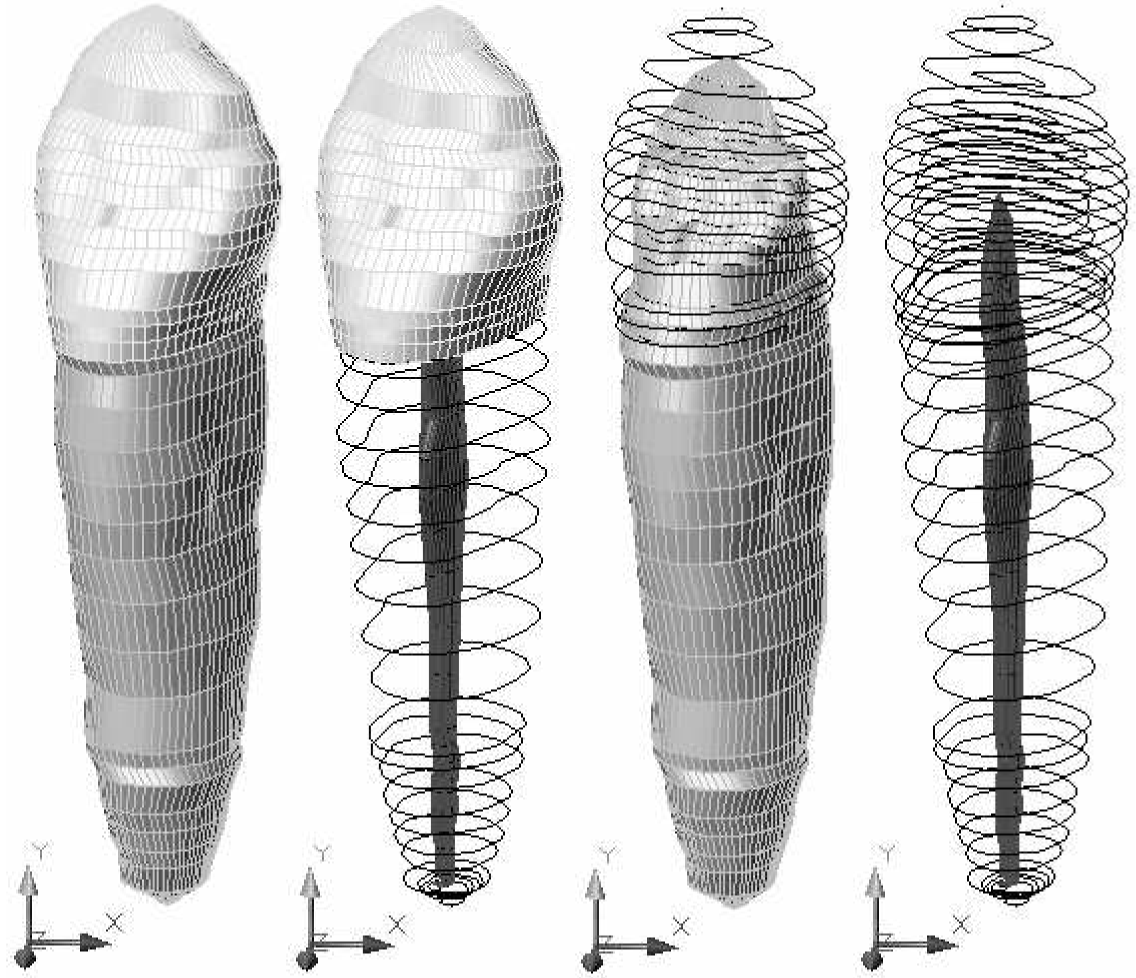

Figure 4. Geometric Model of the Canine Tooth.

In the Finite Element Software (ANSYS^{TM}) the mesh can be generated, and the material properties as well as the boundary conditions, forces and temperatures can be prescribed.

4. Discussion

The advantages and disadvantages of all the studied methods were analyzed, having the method of inclusion and wear proved most effective for our purposes. Besides presenting more viability, the method of inclusion and wear demonstrated more fidelity with respect to size and shape of the internal tissues that constitute the structure of the teeth.

The manual point definition was not considered reliable for our purposes, since the direct drawing can include human error in the literature obtained information, and the lack of detail of the literature data has to be filled by the researcher.

The X-ray method could have been an accurate method, but the superposition that occurs in this kind of scan compromises the identification of the internal tissues of the tooth. For example, particularly the definition of the boundary between dentin and enamel could not be defined by this method.

The computerized tomography would have been the ideal method if the tomography scanner could be reprogrammed with our specifications. Computerized tomography furnishes sliced images of tooth, or even a three-dimensional model of the body under analysis, but the frequency utilized in the scan is not accurate to differentiate between the constitutive tissues of the teeth. For now, it is not possible for us to utilize such equipment only for research purposes, but this would definitely be the right way to go.

Inclusion with slicing also demonstrated itself to be a very good procedure, although more complex than inclusion with wear. The successive cutting of the tooth requires more sophisticated equipment and does not increase resolution of the obtained images.

Inclusion with wear proved itself to be the best possibility for the disposable means, furnishing the best results with the least cost of all methods. Its main drawback is the need to assure parallelism between the worn surfaces.

5. Conclusion

With the methodology developed here problems of interest both of dentistry professionals and biomedical engineers can be analyzed. The methodology of inclusion of the tooth and progressive wear on a model trimmer proved itself to be cost-effective, not too complicate to be achieved, easy to automate, and reliable. With the geometric model generated a finite element mesh can easily be generated.

Increasing the resolution of the images and better controlling the focus and light conditions can minimize the loss of information due to digital representation of real objects. Also, the inherent loss of information from the image vectoring process can be minimized by the choice of the correct number of points and an accurate choice of points.

The methodology developed in this work can be used to help *in-vitro* analyzes of engineering and dentistry problems, as well as to adjust the parameters of a Computerized Tomography Scanner in order to perform non-destructive drawing and consequent mesh generation, allowing for *in-vivo* analyzes.

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