A Model to Simulate the Mastication Motion at the Temporomandibular Joint

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ABSTRACT

The understanding of the mastication system motion is essential to maxillofacial surgeons and dentists in the procedures concerning jaw and teeth corrections. The temporomandibular joint (TMJ), despite its complexity, is one of the most frequently used joints of the human body. The incidence of a great number of injuries in this joint is influenced not only by its regular use during the mastication, but also by the strong forces applied by the muscles and the wide range of movements it is capable to perform. In this work, we propose the development of a jaw simulator capable of reproducing the complete mastication movement. Our jaw simulator is basically composed by three triangle meshes representing the 3D model of the cranium, mandible and teeth; and an anatomically-based joint model conceived to represent the TMJ motion. The polygonal meshes describing the bones and teeth are obtained from CT images and the jaw motion is simulated using the joint model guided by a 3D motion curve obtained from the composition of the standard 2D curves available in the medical literature. The scale, height and width of these original curves are modified to simulate different kind and size of food and to represent the movements' variability depending on patient morphology (teeth, bones, joints and muscles). The evaluation of preliminary results involved the comparison of a dynamic MRI of a healthy person with the respective simulation.

Keywords: joints simulation, motion synthesis, 3D reconstruction from medical images.

1. INTRODUCTION

The knowledge on human jaw (or mandible) motion has influenced maxillofacial surgeons and dentists in the procedures involving jaw and teeth corrections. Besides the problems induced by temporomandibular joint malfunctions, the jaw is considered one of the most exposed regions to trauma in the face. In addition, injuries on the mandible are often not detected, especially when the fracture occurs in the condyle region. The incidence of a great number of injuries in this joint is influenced not only by its regular use during the mastication, but also by the strong forces applied by the muscles and the wide range of movements (6 degrees of freedom) it is capable to produce. The use of jaw simulators during dentist education, orthodontic adjustment of occlusion or preoperative planning of craniofacial surgeries can be very useful, improving the diagnosis and treatment.

The temporomandibular joint (TMJ) is located on both sides of the face in front of the ears, connecting the jaw to the temporal bone of the skull. It is one of the most complicated joints in the human body since it provides rotation (pivoting) and translation (sliding) movements. Despite its complexity, the TMJ is one of the most frequently used joints of the human body, moving at each chewing, talking and swallowing (about every three minutes) movement.

The TMJ system is unique in many ways. The left and right sides must work at the same time to move the jaw. During the mouth opening, lateral and forward movements of the jaw are controlled by the shape of the bones and the action of muscles and ligaments, while the closing end point of the jaw movement is controlled by teeth occlusion. Even more significant, the teeth can be considered as a set of gears connected to this mechanism. The teeth, the structures that surround them and the temporomandibular joint contain sensors connected to the neuromuscular system, which program the way the jaw moves. No other joint in the body has such a rigid end point limit. The proper healthy function of the TMJ system requires normal structure and function of all the component parts, including muscles, nervous system, ligaments, joints (bones, discs and connecting tissues) and teeth (dental occlusion).

During the mastication, the jaw basic motion is more than a rhythmic up-and-down movement. The chewing cycle includes an anterior and a posterior movement, a rotation of the horizontal plane and a lateral jaw deviation[1]. The standard jaw motion of an adult during mastication has a drop appearance in the frontal plane, with a medial opening and a lateral closing, as shown in Fig. 1a. This motion is called Bennett movement[1]. The maximal extension of lateral and vertical movements in the normal mastication is around half of the vertical maximum and lateral movements possible. The antero-posterior jaw movement described by the sagital view is shown in Fig. 1b, while the pattern of jaw movement observed from a horizontal, top-view perspective is represented in Fig. 1c.

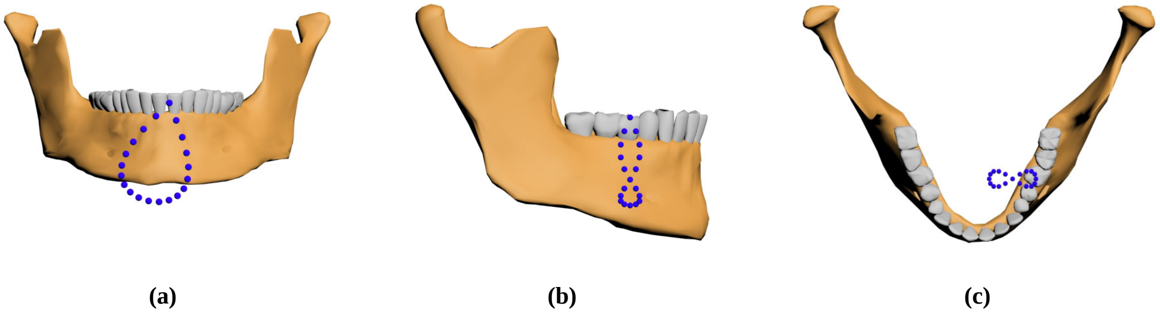

(a) **(b)** **(c)**

Fig. 1. The standard curve that determines the jaw motion based on the *Bennet movement* (a) and on the studies made by *Gibbs and Lundeen*[3] (b and c).

Although the mastication cycle can be represented by the standard curve shown in Fig. 1, in fact, the movement changes according to individual characteristics, including dental occlusion[4] and number of teeth[5], as well as is affected by food type and size[6]. Personal and circumstantial differences in the mastication cycle have been studied by several researchers in the last few years[7-8]. In these studies, experiments were made tracking the different patterns of jaw movement, especially those concerning to chewing foods with different textures.

This paper presents a model to simulate the articular motion in 3D based on the joints anatomic characteristics, and a method to obtain the datasets, reconstruct the 3D model and simulate the mastication movement. The concepts and methods presented in this work will be used in the development of a virtual reality tool to assist the education of dentists on adjustment of occlusion as well as for preoperative planning of craniofacial surgeries.

Next section briefly presents related work on anatomically-based joint simulation. Section 3 presents the methods adopted for data acquisition and 3D model reconstruction and for the simulation of the TMJ motion: the joint model developed and used in this work; the 3D motion curve; and collision detection between the teeth. Section 4 presents the results obtained with the simulator while in Section 5 we discuss the results and ongoing work, and draw some conclusions.

2. RELATED WORK

We can identify two main streams in the study of articulated bodies. One addresses the modeling of joint systems in order to obtain articulated bodies at different abstraction levels, while the other research line is directed to track the correct behavior of real joints in terms of movement. In this section, we briefly review works representative of these two classes of problems.

In graphics applications, the human articulated motion is usually simulated using the same methods developed to support applications based on mechanical joints, as in robotics. However, human articulations are, in many aspects, much more complex. A generic joint is able to describe any kind of relative motion between two or more adjacent segments (links) of the body. Such motion can be given by: (a) a rotation around one arbitrary axis; (b) a composite rotation around two or three axis; (c) a translation in one to three Cartesian directions; (d) rotations associated to translations; and (e) an axis sliding during rotation.

The first models conceived to represent articulated joints for human characters were based on the studies of kinematics of robotic manipulators[9]. Then, schemes like H3D described by Boulic *et al.*[10] were presented in order to provide a mechanism to maintain some topological structure. In the H3D joint model, each joint has only one rotational or translational degree of freedom (DOF). In this way, building a joint with two DOFs like the wrist, for example, requires the creation of two joints. APJ, the acronym for Axis-Position Joint, was proposed by Zeltzer *et al.*[11] and extended by Silva *et al.*[12]. This scheme uses a local reference frame to define position and orientation of a joint in relation to its parent in the body tree. Recently, Maciel *et al.*[13] and Shao *et al.*[14] presented two models for the representation of general joint models that are capable of representing the complex behavior of joints in articulated figures. The joints are changeable to change the axes of rotations during the movement, and its position and orientation can interfere in the motion ranges of other joints, situation often present in the kinematics of real anatomic joints.

Biomechanics usually represents joints using several non-orthogonal, arbitrary axes of rotation[15] which can be easily adapted to model human articulations. The knee joint which is traditionally represented as a single DOF is modeled with a translational center of rotation[13-16]. To model the shoulder joint it is necessary to consider the closed loop consisting of the clavicle, scapula and thoracic surface of the rib cage, which creates a coupling between the articulations of all these joints. Maurel and Thalmann[17] developed a model where the scapula is linked to the thorax by a 5 DOFs joint – three rotational and two translational – while the other three shoulder joints are 3 DOFs joints. The motion is then applied only in the scapulo-thoracic joint, while in the others it is derived from the scapula position. Other structures exhibit a high degree of coupled behavior, like the human spine with the tightly coupled vertebrae. Monheit and Badler[18] exploited this fact to develop a kinematics model of the human spine that exhibits flexion/extension, lateral bending and axial twist rotation**.** In conclusion, the modeling of joints with the maximum of accuracy, in both biomechanics and computer graphics literature, has focused on simulating a set of related joints or a specific complex joint.

Concerning the 3D modeling of the specific motion involving the mouth opening and closing, Enciso *et al.*[19] proposed a method which applies the 3D motion data obtained from an ultrasonic jaw motion tracker to the segmented mandible of a craniofacial model reconstructed from a CT sequence. Their approach to capture jaw movement uses ultrasonic sensors attached to a head-frame and emitters firmly attached to the mandibular dentition. The advantage of this system is that it is a non-invasive, easy-of-use method. The tracking system provides a positional accuracy of ~100 µm and 3D motion capture in real-time. Fushima *et al.*[20] reconstructed the TMJ based on real and kinematics data to analyze specifically the TMJ intra-articular space variation during mastication. The reconstruction of the joint anatomy was based on tomographic data and the real mandible movement was recorded with a non-invasive tracking device.

In this work we are combining the two classes of works described in this section, i.e., we are addressing the modeling of joints in a general sense, and use the TMJ as a study case. In the next section we explain (a) how we reconstructed a 3D geometric model from a tomography of a subject that volunteered for a detailed CT; (b) the mastication curve obtained from the literature and its refinement; (c) the anatomically-based joint model proposed herein; and (d) the use of our joint model combined with the mastication curve to generate mandible movements.

3. MATERIALS AND METHODS

We propose the development of a jaw simulator capable of reproducing the complete mastication movement. Our jaw simulator is basically composed by a 3D model representing the cranium, mandible and teeth; and an anatomically-based joint model conceived to represent the TMJ articulation motion.

3.1. 3D Model Reconstruction

Acquisition. Data was acquired on a PQ5000 CT scanner (Marconi Medical Systems, Cleveland, Ohio) with 1.0 mm slice spacing and thickness, 24.0 cm FOV. Images are 512 x 512 pixels, each pixel representing 0.4687 mm. The total set contains 252 axial slices (12 bits/pixel grayscale information) in DICOM format. The acquisition protocol was chosen from a preset protocol menu (120 kVp, 100 mA, 15.7 seconds). To facilitate the distinction of structures during the reconstruction procedure and avoid the teeth occlusion, the volunteer's mouth was kept open by means of three LEGO® blocks (around 3 cm) between her mandible and superior teeth (Fig. 2, left), allowing to obtain better teeth shape accuracy.

Reconstruction. In order to reproduce and visualize the mastication movement, we need the mandible as a separate object from the rest of the head. The 3D model was planned as three triangular meshes, one for the mandible, and the other two for the superior teeth and the cranium, respectively. To obtain these meshes, firstly a segmentation process was carried out, and then a mesh extraction technique was selectively applied. These procedures were performed using the program SLICER[21] (Fig. 3), a free, open-source software available for visualization, registration, segmentation, and quantification of medical data.

The method we followed for separating the regions is summarized below. All the steps were accomplished with interactive functions provided by the SLICER program:

1. The slices were segmented using a threshold interval of [1,411; 4,095] for separating bones and teeth. The pixels in this interval were assigned red color (Fig. 3b).

2. To separate the superior teeth region from the rest of the cranium, we converted the pixels of two slices back to the original grayscale values (Figs. 3a and 3c). The slices were selected based on a location adequate to separate the desired region. The pixels in this region were assigned magenta values.
3. The pixels corresponding to the mandible are well separated from the rest of the cranium. They were assigned yellowish color.
4. The cranium bones were isolated from the brain region by means of successive interaction using cutting planes and color assignment. The final bone region was assigned blue color.
5. The Marching Cubes[22] algorithm available in SLICER was used to selectively extract the three 3D meshes, each one identified by a specific color (Fig. 4).

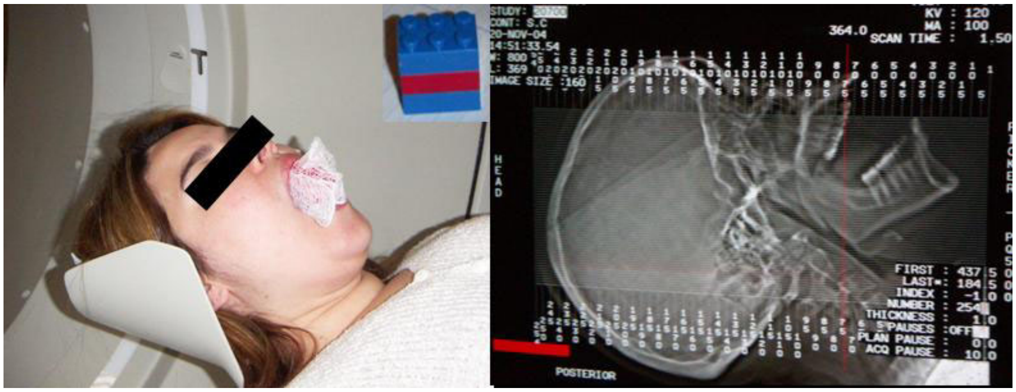
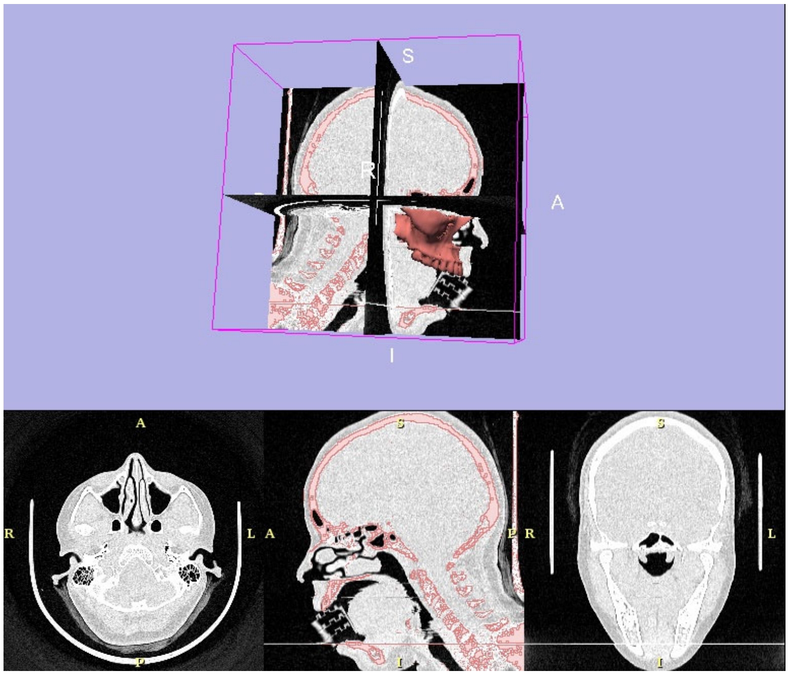


Fig. 2. The volunteer kept the mouth opened during the tomography



(a) (b) (c)

Fig. 3. Views used during the separation of interest regions. Volume was segmented considering bones and teeth (region in red). Slices in (a) and (c) were converted back to grayscale to allow separation of the superior teeth area.

Typically, the surface model generated by the Marching Cubes algorithm is highly detailed but unfortunately composed by millions of triangles. The decimation algorithm[23], also available in SLICER, was used as a polygon reduction technique yet preserving the original topology and forming a good approximation of the original geometry. Due to the need of high resolution for dealing with collision between teeth during simulation, the mandible and superior teeth meshes have higher accuracy than the mesh of cranium bones. They have 97, 105 and 115 thousands triangles, respectively.

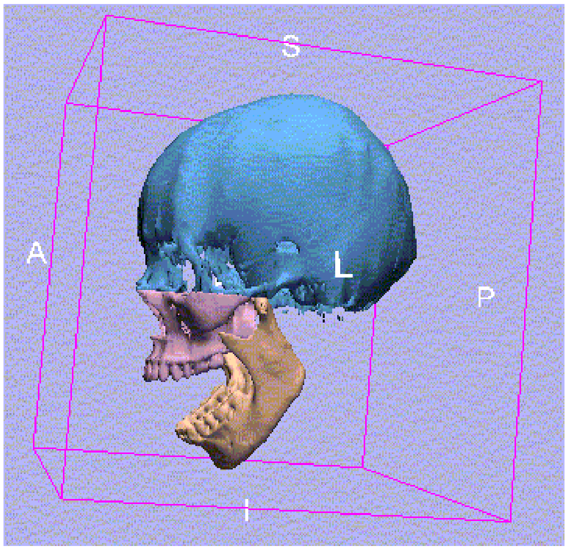


Fig. 4. The three meshes representing the cranium bones, superior teeth area and mandible

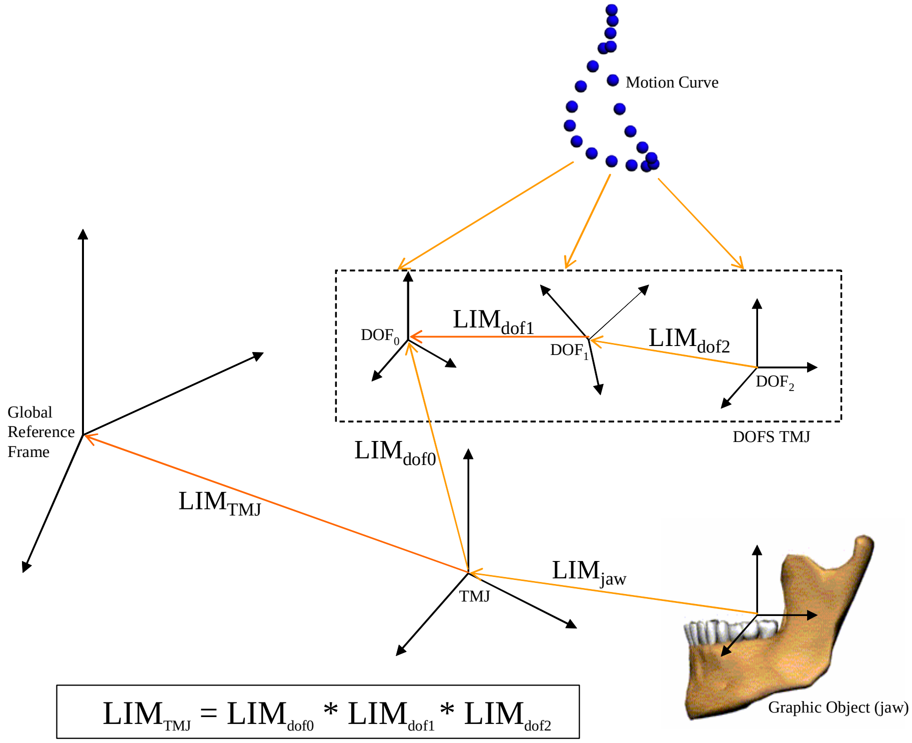
3.2. The TMJ model

The anatomically–based model[13] we adopted in this work was developed to represent either a whole articulated human skeleton, or just part of it and is intended to support medical applications. Our model represents an articulated system as a tree where joints (the main structures of the model) correspond to the nodes, and the body segments (only bones, in this case) are the edges of the tree. Every joint in our tree has a 4x4 homogeneous matrix, called LIM (Local Instance Matrix), in order to establish the relationship between a child and a parent joint in the data structure. Therefore, each joint is defined in its parent reference frame, except the root joint, which is defined in the global reference frame. Graphic objects, like the polygonal meshes presented in Section 3.1, can be associated to each joint in the tree. These objects have a LIM that defines its position in relation to the joint, and are intended to represent bones or any other human body structure which changes according to the joint position. When position and orientation of a graphic object in relation to the global reference frame is needed, e.g. for exhibition, they can be obtained by multiplying LIMs of all joints, from the root to the current joint and the object's LIM. This process generates a GIM, the Global Instance Matrix of that object.

In our model, a joint represents a set of possible movements that are defined according to its degrees of freedom (DOF). The presence or not of a DOF in a joint, defines if the joint is able (or not) to allow a specific movement. A two DOFs joint, for example, determines two kinds of movement, e.g. flexion/extension or adduction/abduction. The implementation of joints with different DOFs in our model is performed by the Dofs (in minuscule). Besides the joint, Dof is one of the most important structures of this model. Basically, to each Dof structure corresponds: its rest position, its maximal, minimal and comfortable angular limits; and the axis where the motion will be done. To flex a joint, we should send it a new flexion parameter (a floating-point normalized value) that is used to determine the new current angle to the joint flexion Dof.

As a joint LIM describes a reference frame positioned and oriented in relation to the parent of the joint, moving a joint is the same as modifying its LIM. In order to make the desirable changes in a joint LIM we use its Dofs. Every Dof also owns a LIM, which describes a Dof local reference frame and is based in the parent Dof. For the first Dof of a joint, which does not have a parent Dof, the LIM describes a Dof local reference frame based on its parent joint. So, the LIM of a joint is regenerated from its Dof's LIMs every time some movement occurs.

In Fig. 5, we can observe the hierarchy of Dofs and LIMs, representing the TMJ. The graphic object representing the jaw is attached to the TMJ and also has a LIM, indicating its local position in relation to the TMJ. During the mastication, each Dof of the TMJ receives its corresponding quantity of rotation and translation that is defined by the motion curve (described in the next section) and updates the TMJ LIM. Finally, the new position and orientation of the jaw can be obtained by recalculating its global instance matrix (GIM). It is simply accomplished through the multiplication of the TMJ LIM by the jaw LIM.



$$\mathrm{LIM}_{TMJ} = \mathrm{LIM}_{dof0} * \mathrm{LIM}_{dof1} * \mathrm{LIM}_{dof2}$$

Fig. 5. The joint model to reproduce the mastication motion for a TMJ

3.3. The mastication curve

To simulate one mastication cycle we determined a 3D parametric motion curve (Fig. 6), which was obtained composing the standard 2D curves shown in Fig. 1. Though the curves' description available in the literature is merely graphical, we observed that the movement can be represented by rotations in the x and y dimensions and a translation in the z dimension. So, we empirically defined the parametric equations that describe the behavior of these parameters as

$$R_x(u) = \sin(u*2)*c_x,$$
$$R_y(v) = \sin(v)*c_y,$$
$$T_z(v) = \sin(v*2)*c_z,$$

where $u \in [0;\pi]$, $v \in [0;2\pi]$, and c_x, c_y and c_z are coefficients that may be modified to obtain different patterns due to food size and texture.

On each movement time step the new rotation in *x* and *y* and a translation in *z* are computed and used to update the local instance matrix of the TMJ Dof structure.

However, we can not directly apply the standard mastication curve described here to every mandible. Before that we need to adapt the configuration of the TMJ (i.e., the Dofs rest position, its maximal and minimal angular limits) to support the curve and the topology of the specific mandible we intend to simulate. Depending on the teeth, bones and jaw morphology the TMJ limits change. Basically, to find the correct TMJ configuration for a specific mandible we need to determine the exact position and orientation of the TMJ articulation in relation to its parent joint at the beginning and at the end of the chewing cycle. These two moments correspond to the instant in which the superior teeth collide with the inferior ones.

The determination of the TMJ position and orientation at these two end points is performed in a pre-processing phase. The standard mastication curve is applied to the desired jaw model and the simulator runs with the collision detection module activated. When a collision between superior and inferior teeth is detected, the TMJ articulation parameters mentioned before are updated.

Regarding collision detection, we adopted the Coldet library[24], a free collision detection library which uses Oriented Bounding Boxes (OBB) hierarchies to guarantee accurate results, as needed in games development, where precise collision detection between two 3D meshes is important.

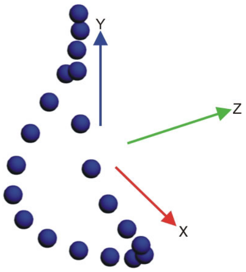


Fig. 6. The jaw standard motion curve during a mastication cycle

4. RESULTS

The anatomically–based joint model used in this work was integrated in the VPat ("Virtual Patients") framework[25], which has been developed to support the implementation of computer graphics medical applications. VPat is an objected-oriented framework providing basic classes that can be shared or extended, allowing the development of more specialized classes to implement, for example, complex algorithms of visualization or motion simulation. The representation of a virtual scene is fundamental for the implementation of a graphic system. A *VPScene* object is composed by a set of graphic objects *(VPGraphicObj),* lights (*VPLight)* and virtual cameras *(VPCamera)*. The exhibition process was conceived based on the MVC pattern, which consists of classes frequently used in interactive systems for building user interfaces. The implementation of a MVC (*Model-View-Controller*) pattern[26] keeps the system functional kernel independent of the interface, which is very useful when the interface needs to be adapted to suit to new platforms or new interaction devices.

We build a VPat application implementing the simulation of the TMJ movement in mastication (Fig. 7). To visualize the results, we used the VTK framework[27] and, consequently, graphic objects were instantiated from a specific class which extends the *VPGraphicObj* class, the *VPVtkObj* class.

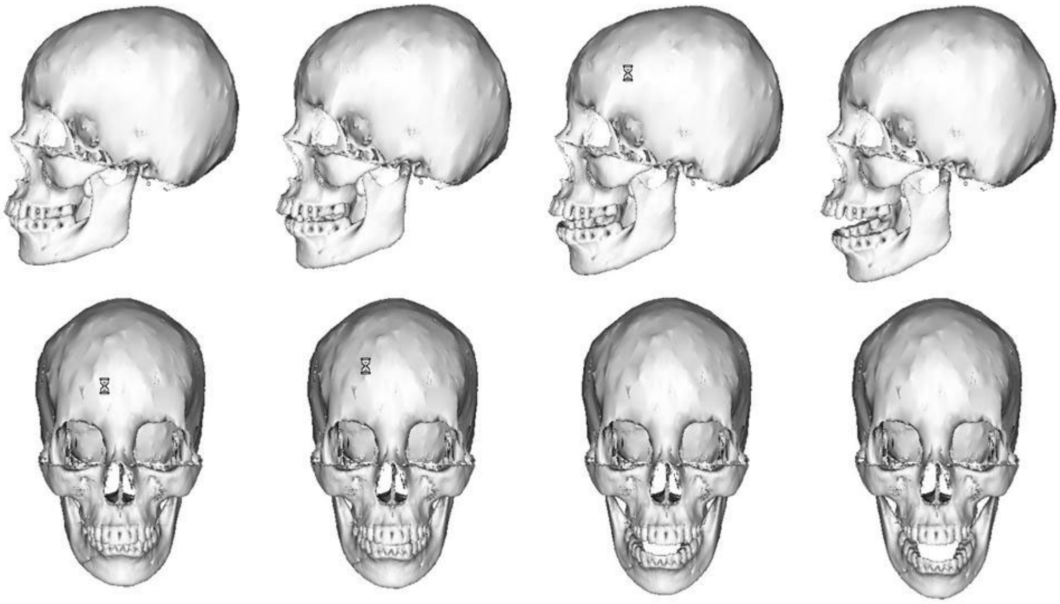


Fig. 7. Four frames of the mouth opening during the mastication: lateral and front views

Some first results we obtained can be seen in Figs. 7 and 8. In Fig. 7 we show four frames of the mastication cycle representing the mouth opening. The sequence is presented from two different point-of-views (frontal and lateral views). A video with the same sequence can be downloaded from the VPat web page (http://www.inf.ufrgs.br/cg/vpat).

The evaluation of these initial results involved the comparison of a dynamic MRI of our volunteer subject with the respective simulation, as can be seen in Fig. 8. Analyzing the condyle region in these images, it is possible to observe that our first results are quite good visually.

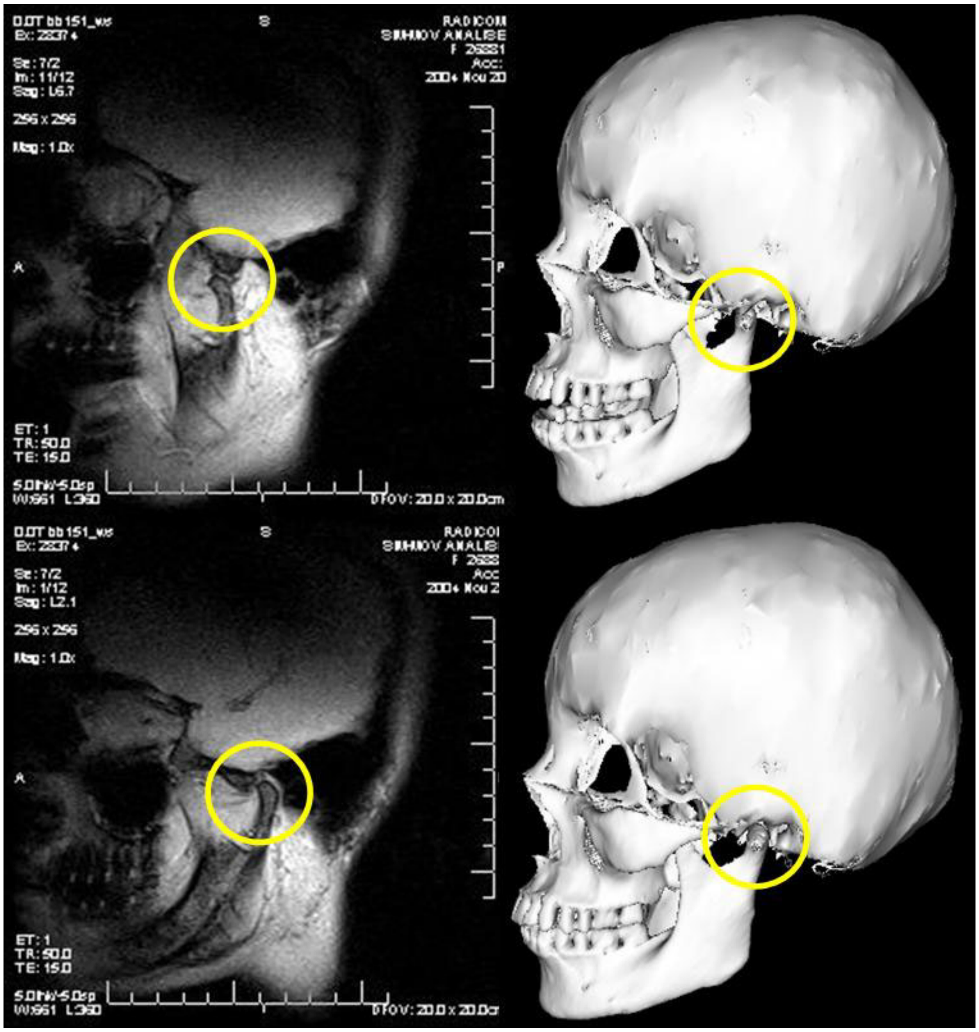


Fig. 8. Two frames of the TMJ simulator (right) compared with the respective dynamic MRI images (left)

5. DISCUSSION AND FINAL COMMENTS

This work proposed a model for the representation and simulation of the temporomandibular joint that addresses specifically mandible movements involved in the mastication cycle. Although most mandibular functions involve only a small range of mouth opening, the maximal position that the jaw can reach at the frontal, saggital and lateral planes produce a wide range of movements (up to 6 degrees of freedom considering the sliding of the jaw condyles).

The chewing cycle can be divided into three phases: (a) the opening phase, the closing phase and the occlusal phase[28] (Fig. 9). So far, this study has considered only the opening and closing phases, i.e., jaw movements without occlusion, which present very high inter- and intra-subject variability. In terms of functionality, however, the occlusal phase can be considered the most important one, since it determines the efficacy of triturating food. The complex movements at this phase are difficult to measure and, as a consequence, they are not elucidated enough to allow a straightforward simulation.

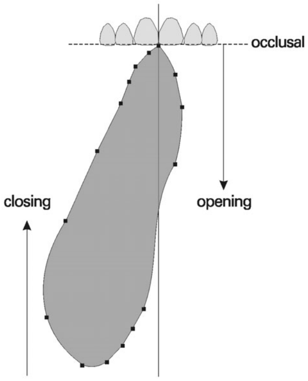


Fig. 9. The masticatory cycle

Regarding the validation of our model, including the occlusal phase, we planned an experiment where the same subject from which the CT data was acquired will be filmed during several chewing sessions with markers fixed at some teeth. Based on these films, we intend to reconstruct different 3D mastication curves and use them in our simulator. The curve variations will take into account the food size and texture used during the tests. The comparison between the curves described by the markers, and reproduced from the acquired film shots, and the simulated ones will allow a conclusion about the accuracy of our model.

Another future experimental study intends to simulate different types of masticatory strokes, based on the different Ahlgren's[2,29] classification of masticatory movements, as shown in Fig. 10. For that, we need to acquire new 3D models from different patients, in order to represent different cranium, jaw and teeth morphology, which conform to the different movements. In doing so, we will be able to build an effective virtual reality tool to assist the education of dentists on the adjustment of occlusion and preoperative planning of craniofacial surgeries.

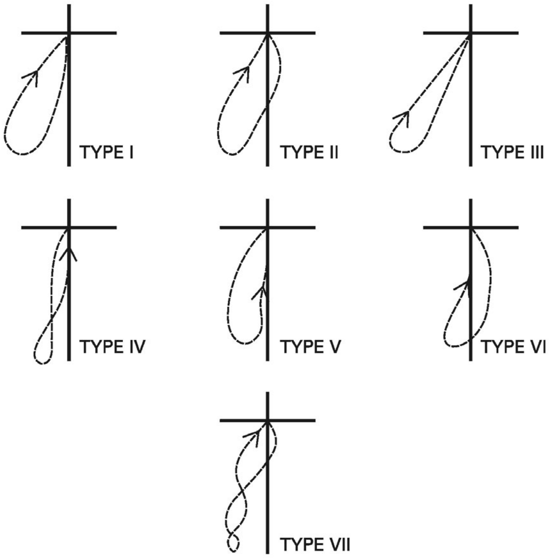


Fig. 10. The Ahlgreen's classification of masticatory movements in frontal plane

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