Three-Dimensional Temporomandibular Joint Modeling and Animation

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The three-dimensional (3D) temporomandibular joint (TMJ) model derives from a study of the cranium by 3D virtual reality and mandibular function animation. The starting point of the project is high-fidelity digital acquisition of a human dry skull. The cooperation between the maxillofacial surgeon and the cartoonist enables the reconstruction of the fibroconnective components of the TMJ that are the keystone for comprehension of the anatomic and functional features of the mandible. The skeletal model is customized with the opposition of the temporomandibular ligament, the articular disk, the retrodiskal tissue, and the medial and the lateral ligament of the disk. The simulation of TMJ movement is the result of the integration of up-to-date data on the biomechanical restrictions. The 3D TMJ model is an easy-to-use application that may be run on a personal computer for the study of the TMJ and its biomechanics.

Key Words: Temporomandibular joint, three-dimensional visualization, TMJ intra-articular space, biomechanical visualization, craniofacial surgery

The temporomandibular joint (TMJ) is a complex anatomic and functional entity. The TMJ’s function depends on the correct postural and functional relationship of its parts. The synergy of such components of the stomatognathic system plays a major role in TMJ’s dynamics. The correct function of the TMJ depends on the neuromuscular function and the biomechanical restrictions that initiate and guide mandibular motility as the temporomandibular ligament, the retrodiskal tissue, the articular disk, the lateral ligament of the disk, and the synovial membrane and fluid. The complexity of the biomechanical restrictions and TMJ motility require an accurate comprehension of its function and dynamics. Three-dimensional models for TMJ reconstruction represent a novel system of visualization and simulation of TMJ anatomy and function.

The acquisition of images through computer tomographic scan and magnetic resonance imaging (MRI) does not actually allow adequate fidelity of TMJ structures, because of poor image definition or overlapping of the frames, especially connective tissues.

The present work introduces a biomechanical model in a virtual reality ambient with the integration of three-dimensional (3D) reconstruction of the cranium (static visualization) and the articular movements of the TMJ (animation).

The starting point of the 3D TMJ model is digital high-fidelity acquisition of a human cranium by digital camera (Fig 1). This process grants an accurate 3D reconstruction of the cranium. The digitized cranium is then elaborated to obtain the polygonal clusters, and those corresponding to the mandible are separated (Fig 2).

The representation of TMJ movements in terms of mathematical functions is based on the principles of the biomechanical restrictions described by many studies in international literature. The result is an easy-to-use software that may be accessed on the Internet by a personal computer for academic research and, at the same time, a valuable instrument for better understanding of diagnostic approach to the physiopathology of the TMJ.

The 3D TMJ Project stands as a novel instrument that applies virtual reality and biomedical principles onto the comprehension of the dynamics of the TMJ (Figs 3A, B). The evolution of the studies in the TMJ and the progress in the field of virtual reality (virtual tour) grant future expansion to this application. Three-dimensional TMJ is a scientific instrument for better understanding of the TMJ both its physiology.

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1526
and its pathology. Future updates of the project may lead into the challenging field of TMJ navigation and surgical simulation.16,17

**MATERIALS AND METHODS**

The 3D TMJ Project is based on a basic principle; the motility of the human body may be attributed to the mathematical functions revealing the movement of the single bone, interacting one with the other.

The project moves from the acquisition of data of a real cranium using the 3D photographic technology “virtual” object derived from customized 3C Lab process. This technology allows, with the use of a personal computer, to rotate an object on its longitudinal axis. The cranium rotates 10 degree at a time, and the result is its complete acquisition as a sequence of 36 images; each image with a rotation of 10 degrees in comparison with the preceding and the sequent. The system then scans every image to create an arrangement of points in a coordinate system \((x, y)\). Once the bidimensional scan of the images is complete, the points in the bidimensional coordinate system are interpolated to one another. Successively, a series of extrapolation calculations brings to the tridimensional model of the cranium.

Once the 3D virtual cranium is designed, a complete set of physiologic movements must be provided to the system to obtain a virtual reproduction of its motility. The tridimensional model is realized as a series of coordinated polygons, each representing 1 distinct anatomic structure of the cranium. We selected the coordinated polygon representing the mandible and applied to it the physiologic plan of movements of the mandible.

The axial array is used to define the elementary rotational axis \((x, y)\) passing through the superior edge of the mandibular condyles; the second rotational axis is the 3D axis \((x, y, z)\) going through the condylar insertion of the temporomandibular ligament. This axis intermingles the sagittal axis (Figs 4A, B); the latter provides the anteromovement of the mandible, keeping the distance between the condyle and the temporal bone equal to 3.5 mm.

The mandible maximal opening was stopped when the intercuspidal distance of the incisors was 45 mm (Fig 5).

The 3D mathematical model simulating the opening and closing of the mandible is now complete. The modeling of the disk, the ligaments, and the remaining soft tissues is then supervised by the maxillofacial surgeon and completed by an animation artist.

The articular disk, the retrodiskal tissue, the lateral disk, and temporomandibular ligaments are reproduced in the 3D virtual reality. These structures and their motility and structural changes are yet dependent on the mathematical model of the movement of the mandible.
The retrodiskal tissue is inserted onto the surface of the mandibular condyle and the glenoid cavity in the 3D model. In this way, the protrusion of the mandible causes expansion of the retrodiskal tissue, mimicking reality (Figs 6 and 7). The disk and the lateral and medial ligaments are connected to the medial and lateral sides of the condyle (Figs 8 and 9); the temporomandibular ligament is fixed on the lateral surface of the zygomatic tubercle and to the lateral region of the condylar cartilage, as suggested in the literature.\(^6,18\)

At this point, the artist customizes the 3D model with color textures for adequate photorealism.

The 3D model is ready for video editing and virtual tour. The latter is a modern technology from naval application. Virtual tour is an ambient reconstruction in virtual reality, featuring 360-degree visualization in the space. Simply moving the mouse and the point of view of the operator to tour the 3D cranium with the use of the mouse, 3D TMJ enhances movements of the mandible and modification of the rotational and translational axis, displays connective anatomic structures, and moves the TMJ on the basis of its biomechanical restrictions.

**DISCUSSION**

The TMJ features a complex anatomic architecture. The close distance between the structures and their framework makes the accurate TMJ visualization a difficult task, especially the connective component of the joint.

The 3D TMJ virtual model enhances the comprehension of the physiologic biomechanics of the TMJ. Three-dimensional TMJ models have already been applied in the study of the anatomic aspects of the
The work of the cartoonist has been fundamental for the reconstruction of animal models starting from the fossils and their realistic movements.

The ideal 3D model represents a replica of the real form. Three-dimensional computed tomographic (CT) scanning and MRI have been used for visual representation of movement. However, the accurate depiction of motion would require at the time an enormous amount of scans, one for each position of the anatomic structures involved in the movement. The high dose of radiation and the cost and time for such analysis are much too high for routine.

The virtual techniques based on the acquisition of static frames rest on the capability of the operator to furnish the exact motion and the relationship among all the anatomic components. Such method does not ensure the best results in terms of fidelity.
The 3D TMJ Project stands on the principle that human body movement may be reproduced as a series of mathematical functions. Each function describes the interaction of a single anatomic component relative to the others. The mathematical model is applied in consideration of the TMJ physiologic biomechanics.

Many authors describe the physiology of the rototranslatory movement of the mandibular condyle and the articular disk. Osborn illustrates the function of the temporomandibular ligament. The anatomic aspects of the retrodiskal tissue and its protective function on the condyle during movement are explained in the work of Kino et al.

The analysis of the biomechanical restrictions guiding the mandibular function makes possible the application of virtual reality modeling and customization of the mandibular function on the basis of a mathematical project. An example of this is the transposition of the mandibular rotatory axis on the insertion of the temporomandibular ligament; this ligament is inextensible; thus, after rotation, it forces the mandibular condyle to move forward and then downward, following the plane of the zygomatic tubercle.

Many aspects of the physiology and the anatomy of the TMJ are yet to be cleared; in consequence, our virtual model may not describe all the physiologic variations of the TMJ during movement. The 3D TMJ is an ongoing project. The progress of such project rests on the capability of the system to elaborate mathematical data and reproduce a 3D reconstruction. The actual and future scientific data on the TMJ will be integrated into the system. Three-dimensional TMJ was thought to elaborate up-to-date data on the basis of the physiologic and anatomic findings yet to come. As a result, 3D TMJ enables the visualization of the virtual reconstruction on a common personal computer or a notebook.

The recent technology called *virtual tour*, widely diffused in nautical applications, may be shaped to guide the user into a virtual comprehensive demonstration of the human body and the related function of one or more of its parts as the TMJ. The use of a mouse allows the user to explore the virtual model of the TMJ at rest or during its rotational and translatory movement.

Next step will be the customization of the system through the identification of the 3D coordinates \((x, y, z)\) of the TMJ of a single individual from CT scans and MRI, their acquisition into the 3D TMJ system, and the integration with the connective components of the TMJ. This will lead to personal virtual reconstruction of the TMJ, for the study of the physiologic aspects and the pathologic changes in the TMJ of any patient.

**CONCLUSIONS**

The 3D TMJ model is a novel system for TMJ visualization and functional biomechanics. It is the result of a cooperation between the maxillofacial surgeon and a society for nautical 3D project and virtual touring. The result is a simple and easy-to-use software that enables the user to have access to the TMJ both as an anatomic structure and as a functional system in relationship with the stomatognathic apparatus. Temporomandibular joint animation was elaborated through the application of mathematical functions to the biomechanical restrictions of the TMJ as described by many authors.

The use of a mathematical model allows continual update of the system on the base of new and forthcoming knowledge of TMJ anatomy and function. The application of virtual touring enables 3D ambient navigation and TMJ interaction from the insight.

As a result, the 3D TMJ Project represents a valid system for academic and diagnostic approach to the study of TMJ physiology and pathology through its statics and dynamics. The software may be expanded for the use on all human joints.

To date, we are working on customization of the skeletal model by means of CT scans and integration of the connective components of the TMJ, thanks to the collaboration between the maxillofacial surgeon and the artist for individual customized animation.
REFERENCES