Simulation of Jaw-Movements for the Musculoskeletal Diagnoses

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Simulations of human body functions or movements are getting more important as the complexity of operations increases. The preoperative planning of craniofacial operations like the repositioning of the jaw is an example for such operations. Here, but also in other medical fields, simulation can help to estimate the results of a procedure or can facilitate the diagnosis by a better view of the anatomy and pathology of the patient.

The goal of our research is the development of a graphical simulation of the human mastication system to give the surgeon an impression on the inner anatomy of his patient. This virtual view on the pathology and the possibility of simulating the postoperative results enables a simplification and improvement of the preoperative planning.

The main focus of this paper is the introduction of a kinematic model of the temporomandibular joint. This kinematic model describes the geometrical and analytical movement of the jaw by specially defined axes. It is the basis for an animated simulation of the mandible movement. Through integration of the muscles and muscle forces, we come to a realistic dynamic simulation of the whole mastication system.

1 Introduction

With the complexity and importance of todays' maxillofacial and craniofacial operations the need for pre-operative planing and simulation tools increases. The required accuracy of such operations is within a millimeter and deviations can be responsible for success or failure of an operation.

Currently, 3D visualization systems of the static tomographic images are used for diagnosis and treatment planning. This is an improvement to the use of slice images as they are produced by the tomographic devices. But besides that, it is also very important for a surgeon to get an impression of the functional effects of the actual operation to the patients anatomy. Static images require a much larger imagination of the surgeon than dynamic 3D images.

An example for such an operation is the repositioning of the mandible (lower jaw) to correct deformations of the chewing system in the craniofacial surgery. Maxillofacial deformations cause musculoskeletal pain or pain in the temporomandibular joint. This operation is performed using a technique called the sagittal dissection. For the diagnoses the physician usually observes the movement of the jaw and the occlusion which is the
contact between the mandibular and the maxillar teeth. A functional simulation of the moving mandible is a step to a precise 3D planning of an operation and a prediction of the post-operative results as well as the functional stability.

The goal of our research, which is part of a cooperation project in computer-aided surgery between the University of Karlsruhe, the University of Heidelberg and the German National Cancer Research Center, is to build a dynamic simulation system of the mandible and the mastication muscles. Such a simulation can help the physician in diagnoses, as it allows a direct visualization of the inner tissue and bones while a movement is being performed. At the same time this simulation system can be extremely useful for prediction of the post-operative results. This paper presents an approach to model the kinematics of the temporomandibular joint (TMJ) and to simulate the human mastication apparatus. Furthermore it describes the graphical simulation of this system by visualizing mandible and muscle movements.

2 State of the art

Due to its importance, the temporomandibular joint has been an area of active research in dentistry for many years. The main reason for this is the strong influence of this joint on the occlusion [7]. An optimal occlusion is the goal of any dental therapy. Dysfunctions in the area of the TMJ entail a disorder of the occlusion like the supernatural wear, loosening of the teeth, and severe pain disorders.

Whenever joint motions are simulated, kinematic models have to be established, e.g. for human joints in [2], [5]. Some of these projects come from the movie industries to animate computer models. These kinematic models are relatively simple if single rotation axes for each joint can be identified. For most human joints, this is a suitable approach. However, due to its complexity, the temporomandibular joint can not be modelled in this way.

To get a better view on the occlusion, physicians use articulators. In these mechanical devices, plaster-casts of the teeth are fixed. By adjusting the hinge axis position, the inclination of the trajectory of the condylus, and the Bennett angle [7] the individual geometric parameters of the patient are identified. Articulators are used to show a view of the occlusion and the initial opening and closing movement. They do not allow a precise simulation of a whole chewing cycle. Particularly, the muscular functions can not be integrated in any way.

A research group at the Waseda University in Japan has been working for several years on a chewing robot [11]. The third version of this robot (WJ-3) consists of a skull model which is moved by motors and wires. Its kinematics is fixed and given through the mechanical assembly and the muscle functions are modeled by artificial muscle actuators (AMA). This is the first and only simulation known to the authors, which enables a copy of a whole chewing cycle including muscular functions. Due to the fact that an adaption to the patients individual parameters is not possible, a robot like this can only be used for research in the field of the TMJ. In addition it is not possible to trace trajectories of the patients mandible and repeat them with such a device.

A graphical simulation of the mandible movement is not known to the authors. New tools for visualization of the mandible movement, particularly modelling dynamic aspects are useful in simulation, analysis, and planning of operations. This is especially valuable if the tools enable a simple adaption to the patients parameters and the possibility of reproducing mastication movements of the patient. A simulation enables a better view to the pre-operative situation, facilitate precise pre-operative planning, and make predictions of post-operative results more reliable.
3 Theoretical and anatomical foundations

The temporomandibular joint is considered to be one of the most complex joint constellations in the human body. In contrast to other joints, it is a free hanging system, held by the mastication muscles, the tendons, and the joint capsule. Its movement is restricted by the structure of the muscles, the ligaments, the bone, and the morphology of the teeth. Therefore no fixed rotation axes can be determined for the TMJ. The movement of the jaw can be described as a combination of rotating and gliding of the caput mandible around the os temporale. Finding an appropriate model for the TMJ requires understanding the mandible movement and the possible positions that can be reached by the jaw. We will give a short introduction to the anatomic foundations first before we describe our kinematic model.

3.1 Mandible movement

The movement of the mandible is usually described by the incisal point which is located between the two lower incisors. During a mastication cycle, this point performs a loop starting at the intercuspidal position [11]. The maximal area including all the points the incisal point can reach is described by the Posselt figure. The Posselt figure is the convex hull of all these points and displays the position of the incisal point for the extreme constellations of the joint. We call this the border movement of the incisal point.

![Posselt figure, sagittal (after [7])](image)

The sagittal Posselt figure (Figure 1) can be divided into 4 main segments. In the first segment (the maximal rear opening period), the jaw rotates about 10° around the hinge axis. If the mandible moves further downwards, a protrusion starts. The protrusion is a feed of the condyls on a circular path. Therefore, the final rear opening period (2) can be considered as combinated movement of the hinge axis and a protrusion. After this period the maximal opening is reached. The maximal frontal path (3) can be described as an rotation around the hinge axis by a maximal protrusion. At the upper bound, only a protrusion takes place. If the maximal frontal position is reached, the condyls are located
under the tuberculum articulare. Finally, the jaw is gliding back into its resting position [10].

This is the border movement the incisal point can perform, projected on a sagittal plane. The path of the fourth segment is affected by the structure of the teeth, and the other paths by the muscles and ligaments. Similar to the sagittal Posselt figure, each lateral movement can be divided into two segments: The lateral movement with occlusion and the maximal lateral position during an opening of the mandible (Figure 2). Depending on position or malposition of the teeth, different pathologic movements are possible. The paths can differ significantly from patient to patient.

Figure 2: Posselt figure, frontal (after [7])

3.2 Kinematic modelling

The previous section showed the different partial movements of the mandible: The opening movement around the hinge axis, the combination of opening and protrusion of the condyles, and finally the lateral movement. Each kinematic position of the incisal point can be described as a combination of these three movements.

Due to the fact that the temporomandibular joint is a very complex system, it is an important aspect that rebuilding this joint can only be an approximation and can not include all pathologic aspects. The goal of this kinematic study is to find a good approximation of the TMJ with an accuracy of 1mm. The brute force method to build a kinematic model would be to define the mandible as a manipulator with two joints, the left and right temporomandibular joint. This seems to be a good approach, but contains a major drawback. The two joints are connected via the mandible, thus resulting in a closed-loop chain. The resulting dependencies of the two joints have to be modeled as well, which is difficult and not practicable for further calculations. Therefore, we applied robotic research to the problem of finding an appropriate kinematic model [2], [6]. Our model consists of a sequential open-loop chain with rigid bodies connected by revolute joints. We therefore had to identify the rotation axes for the three basic movements.

A rotation axis for the opening position is intuitively the hinge axis. It is located between the two condyles and can be determined by measurements, as described in [7]. The protrusion or the path of the condyles can be described as a segment of a circle. This approximation is known from studies in dentistry [1], [8] and is caused by the almost
circular structure of the os temporale. The radius of this circle varies from patient to patient from 10 to 15mm and the center is located at the os temporale.

During a left lateral movement of the mandible, the left condylus stays nearly in its position while the right condylus starts a protrusion. As rotation axis for this movement, the connection between the condylus and the rotation point of the protrusion can be considered (Figure 3). This model respects the Bennett angle and the similar rotation to a pure protrusion.

The whole movement is a combination of these basic rotations. The order of the axes follows from the arrangement as a chain (Figure 4). Each rotation and translation is expressed in a homogeneous coordinate representation [6]. A matrix transformation with homogeneous coordinates enables composition by matrix multiplication. For an easy calculation, a rotation is performed only around the three basic axes. Since the matrix multiplication is not commutative, the order has to be respected:

1. The rotation around the protrusion axis \( R_p \) to move the condyles to the right position.
2. The translation \( T_1 \) to the condylus.
3. The lateral protrusion axis \( R_{lp} \) which additionally moves one of the condyles forward and includes the side movement.
4. The hinge axis \( R_h \) for the opening of the mandible.
5. The translation \( T_2 \) to the incisal point.

The frame of the incisal point \( I \), which represents the cartesian coordinates and the orientation, depends on the three rotation angles \( \Theta_p, \Theta_{lp} \) and \( \Theta_{hp} \). The translations are given by the anatomy of the patient.

\[
I(\Theta_p; \Theta_{lp}; \Theta_{hp}) = F_0 \cdot R_p \cdot T_1 \cdot R_{lp} \cdot R_h \cdot T_2
\]

The resulting cartesian coordinates of the incisal point can be calculated and they are already adapted to the anatomical records of a test person.
3.3 Inverse kinematic problem

The above given kinematics can be considered as an abstract model for the human mastication movement. Even if it is adapted to the real biomechanics the three axes cannot directly be compared with three different joints in the human body. Therefore the angles have to be detected by calculating them from the position and orientation of the jaw. This calculation is done by the inverse kinematics of the temporomandibular joint. The inverse kinematic is the inversion of the above shown formula. It calculates $\Theta_p$, $\Theta_{lp}$ and $\Theta_{hp}$, given the cartesian position of the incisal point. Taking into account that the values for $\Theta_p$, $\Theta_{lp}$ and $\Theta_{hp}$ have limited ranges caused by the anatomical structure, the inverse kinematic problem has a unique solution.

Due to the fact that the combination of the three rotations produces complex trigonometric terms the solution cannot be calculated analytically. We implemented and evaluated two different methods to solve the problem of the inverse kinematics:

- Using machine learning [4] we trained a neural network with the kinematic model to find an approximation for the inverse kinematics. This approach is used in robotics for difficult kinematics. The basic technique is to generate a large number of learning data using the direct kinematics. A neural network with three layers and up to 10 neurones in the hidden layer was trained using the generated data set. Special attention was put on the selection of the training data. It has to be guaranteed that the network does not learn the specific values as it would produce wrong results for new values.

But the method also has disadvantages. Training a neural network needs a lot of test data and the results depend on the quality of the training data. Furthermore training a neural network for a general inverse kinematic is hardly possible as every parameter of the kinematics has to be represented by a large number of training data. This would expand the volume of the training data set to an enormous number. Therefore the
neural network has only be trained to a specific patient. These limitations are very strict and not possible for an application in a medical environment.

- Another method is the iteration from a starting guess to the goal position by gradient descent using the direct kinematics. A starting setting for $\Theta_p$, $\Theta_{lp}$ and $\Theta_{hp}$ is guessed from a set of precalculated values. It is adapted recursively to the searched settings. This is done by changing the values for $\Theta_p$, $\Theta_{lp}$ and $\Theta_{hp}$ one by one. Each time the according point is calculated using the direct kinematics. Minimizing the error between this point and the searched point means minimizing the gradient between both. This technique is very fast for three axes and can be used even for calculating a sequence for an animation.

4 Simulation environment

The kinematic model presented above has been integrated into a graphical simulation system. This simulation environment consists of two modules, the modeler and the simulator. In the first step, the user specifies the individual parameters of a patient in the modeler. He can use a default data set which has been segmented from a CT (Computer Tomograph) image [12] or a the specific data set of the patient. After conversion into a triangular surface data set, they can be visualized. This conversion has been done using the Splitting-Box algorithm [9], which is an enhancement of the Marching-Cubes algorithm [3]. A faster visualization was reached by reducing the number of triangles.

Special functions were implemented to allow the definition of the rotation axes and the range of the minimal and maximal angles. The user can do this either interactively using the mouse or textually entering the Cartesian coordinates.

The second module, the simulator, provides the user with special functions for visualizing the movement of the mandible, tracing different points during a movement (see Figure 5), or moving the mandible by changing the angles for $\Theta_p$, $\Theta_{lp}$ and $\Theta_{hp}$. The scene can be observed from every direction.

There are many pathologies which result not only from anomalies of the jaw but of the musculoskeletal system. Due to this fact a simulation system should not only include the rigid tissue. Therefore we included the dynamic properties of the skeletal muscles into the simulation by using muscle models from Hill and Žajac [13]. Force-velocity models and force-length models based on those of sarkomers are used to calculate the movements of the jaw. The parameters for these models are the maximum force the muscles can produce and their length. They were determined by pressure measurements on the teeth or were estimated in this first approach. Another problem has been the geometric representation of the muscles. In reality, the muscles used for chewing movements are attached to a large surface. This problem has been solved by simplifying them as "muscle-threads". Each muscle is replaced by two or more threads, depending on the directions of its movement. This technique allows a division into the main directions of drawing.
5 Results

Experiments have been performed evaluating both, the static and dynamic properties of the model. The static quality has been determined by comparing the path of the workspace of the incisal point with a recorded area (see Figure 6 and 7). The recorded paths from a chewing movement have been used for the dynamic evaluation.

Figure 6 shows the sagittal Posselt figure which was produced using our kinematic model. It is comparable with the records made from the same anatomical assumptions measured by a test person (Figure 7). The differences in the maximal frontal movement of
the incisal point can be explained by the non-linear relation between $\Theta_p$ and $\Theta_{hp}$. In our first attempt, this inaccuracy has been accepted in order to the clinical irrelevance of this region. In future, we will concentrate on the non-linear relationship between the rotation angles.

Further experiments concern the evaluation of the dynamic properties of the model. We are currently comparing recorded traces of the chewing movement of a test person with movements performed by the simulation system. Beside the evaluation of the mandible path further conclusions about the change in the angles of the kinematic model or the change in the muscle length will be possible.

![Figure 6: Posselt figure of the simulation](image1)

![Figure 7: Traced Posselt figure, sagittal view](image2)

6 Conclusion

We have presented a kinematic model of the temporomandibular joint using three rotation axes. This model can be considered to be a copy of the basic movements the temporomandibular joint can perform. Furthermore, an application for this kinematic model, a simulation of the mandible movement, was presented. First experiments and results showed the suitability of our model. Several applications for this system exist. In jaw surgery, e.g. in the craniofacial surgery, including the simulation of cutting a jaw, it is possible to preview the results of a surgery and to assess the location of a cut. Furthermore this system can be used in dentistry. Here simulation of the post-operative jaw movement is of great importance, but is currently done using articulators. This diagnosis can be improved by our computer simulation. Finally this way of modeling is not limited on the jaw. It can easily be adapted to, e.g. the knee, the hip or the ankle-bone.

The current research effort of the authors focuses on refining the kinematic model. An other aspect will be the integration of geometrical muscle models into the simulation which will extend the functional muscle model ("muscle-threads") by a more realistic appearance.
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