FROM JAW TRACKING TOWARDS DYNAMIC COMPUTER MODELS OF HUMAN MASTICATION

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Abstract: In this paper, we enhance the model of the human masticatory system presented in [1] by incorporating prescribed movements of the mandible during a chewing cycle. To obtain realistic descriptions of such movements, we have developed a custom-made brace that allows us to use a motion capturing system typically applied to human movement and gait analysis. In this paper, we give a brief description of the approach to collect chewing data with six degrees of freedom, as well as a short discussion on its quality. These data are the foundation of chewing simulations presented in this paper and allow us to study the muscles of mastication within realistic motion. These simulations are based on solving continuum-based equations of finite elasticity using a Finite Element method with cubic Hermite basis functions. We solve for the deformations of the muscles given the location of the mandible at a sequence of time steps. With the use of the motion tracking system, we can realistically simulate a normal chewing cycle. Most importantly, we have an extensible framework to which we can add more detail to further improve our representation of the mastication process.

Introduction

The Physiome Project aims to provide a framework for modeling the human body using computational methods [2,3]. Such models, which are physiologically accurate enough to be used in hypothesis testing or biological function analysis, should try to incorporate physiological information from different scales, such as from the cell, tissue and organ level. As part of the Physiome Project, we present an anatomically-based computer model of the human masticatory system that provides an initial framework for simulating the complex chewing process. This simulation should be seen as a first step towards the ultimate goal of more sophisticated models that are guided by active electrical muscle activation.

This paper is organized in the following way: In the section "Methods", we describe the set-up of a motion tracking system, which is used to record movements of the mandible while chewing, the algorithm to transfer the recorded data to the computational model, as well as the Finite Element model for solving the deformations of the muscles given a prescribed movement of the mandible. In the section "Results", we present the recorded data by depicting a trajectory of the movement of the temporo-mandibular joint (TMJ). Further, we present reults from our Finite Element simulations, which solve during one chewing cycle for the deformation of the muscles of mastication. In the section "Discussion", we address some of deficiencies of our approach. We conclude this paper with some remarks on future research directions.

Materials and Methods

To obtain a realistic trajectory of the mandible during mastication, we use an opto-electronic tracking system; the motion capturing system VICON MX located at the Biomechanics Laboratory, in the Department of Sports and Exercise Science at the University of Auckland, Tamaki Campus. This system is typically used for human movement and gait analysis. To employ this system for tracking the movement of the mandible, it was necessary to identify a way to fixate special markers to the mandible. The prerequisite is that the markers have to stay fixed with respect to the mandible at all times, even while chewing on tough food samples. The development of a custom-made brace (see Fig. 1) fulfils these prerequisites and enables us to use this system to record movements of the mandible while chewing on food samples. Although we recorded chewing data for different food samples, the main purpose of this paper is to exhibit the process of gathering three-dimensional data with six degrees of freedom that describes a natural movement of the mandible. Further, we address the issue of applying these measurements to our computational model. At this stage, we are not interested in reporting on a clinical-type study involving different food types and subjects. Therefore, we omit in this paper any details on the food sample(s) and our subject(s).

The overall process of data collection is best described by the set-up of the above mentioned motion capturing system. It consists of an upright sitting subject chewing on a particular type of food, eight interconnected high-speed digital cameras, a total of 6 light-reflecting markers, and Vicon's hard- and software analysis system. The cameras are placed evenly distributed at a distance of about 2 meters from the subject. Three markers are located on a headband. The other three markers are mounted on the custom-made brace. Vicon's system set-up is capable of accurately determining the position of the markers with respect to a three-dimensional rectangular coordinate system. As we shall later see, three markers at the headband are enough to track the subject's head movements while chewing. This allows us to correct the position of the mandible, which is characterized by the three markers mounted on the brace, by its respective head movement. Figure 1 illustrates the set-up of the experiment and gives the reader an indication for the locations of the markers on the headband, as well as a close-up of the custom-made brace.

Figure 1: Left: Set-up of the experiments with 6 markers (3 at a head band and 3 on a custom-made brace). Right: Enlarged view of the custom-made brace.

Although this particular system is capable of processing and recording in real-time the location of multiple marker locations at a rate greater than 150 times per second, we found it to be sufficient for our experiments to use a frequency of 100 Hz. We started the experiment by placing a food sample on the subject’s tongue. After the subject closed the mouth, with the food sample still on the tongue, we initiated the recordings and told the subject to start chewing. We stopped the recordings after the subject entirely swallowed the food sample. The duration of this process lasted about 30 seconds. This experiment led to recordings of the location of the 6 markers at more than 3000 time steps. In a next step, we need to link the recorded data, which describe the coordinate positions of the markers within the rectangular coordinate system chosen by the motion tracking analysing software, to a description of the movement of the mandible that can be applied to our model.

The idea is to compute the three rigid-body rotations and the rigid-body translation that prescribe the movement of the marker locations from one time step to the next one. We note that three rotations and one translation are sufficient to fully describe data with six degrees of freedom.

To achieve this, we made several assumptions and observations. First, we consider the mandible as a rigid-body. Although the mandible is a deformable object consisting of a cancellous bone core surrounded by cortical bone, simulations in [1] show that muscle forces acting on the mandible deform the mandible only by small amounts. For our purpose, the displacements are small enough such that they do not play a role and can be neglected. Further, we note that our computational model of the skull was created from data that has similar dimensions as the skull of our subject and hence scaling of any data has not been taken into consideration. As far as our data are concerned, we have to establish a measure for the quality of the recordings. The accuracy of the system is exhibited by computing the distances between the three markers mounted to our brace. Since the markers are glued to the brace, the distance between the markers should not change between time steps and, hence, serves as a good measurement for the quality of the recordings. The standard deviation of the distances between the markers was about 0.15 mm. Moving the cameras closer to the subject would likely reduce this value. Further, we make the assumption that the markers at the headband are fixed with respect to its initial position on the skull and do not move (with respect to the skull) throughout the experiment. This is not quite the case because we use a headband with a material comparable to a sports sweatband. Skin movement caused predominantly by the chewing process is responsible for most of the deviance of the markers with respect to its initial position on the skull. To quantify the amount of deviation, we calculated at each time step the area of the triangle defined by the three markers on the headband. A statistical analysis showed that the standard deviation of the area of the triangles is 1.1893% of the area measured at the first time step, small enough to consider the markers on the skull as fixed.

The process of computing the rigid-body rotations and translation starts by choosing the first data set, consisting of the six marker-coordinates at the first time step, as reference. Then, for each subsequent data set we first determine the rotations and translation resulting from the head movement. To do this, we set up the two planes containing the reference head markers and the head marker of the current data set. Next, we calculate the rotation matrix that maps the plane containing the current head markers onto the plane constructed from the reference head markers. The translation is determined by the difference between the front head marker of the reference data set and the respective marker location within the current data set. This way, we obtain the rigid-body rotations and translation caused by the head movement during chewing and we can correct all the marker coordinates of the current time step by the head movement. A similar algorithm is used to compute the rotations necessary to map the plane spanned by the lower markers of the current data set (corrected by the head movement) onto the plane spanned by the lower reference markers. The translation is obtained by the difference between the middle reference marker and the rotated middle marker of the current data set. Note that choosing the middle marker as basis for computing the translation is arbitrary. We also could have chosen any of the other two markers. Any rotation can be decomposed into three independent rotations and described as azimuth, elevation, and roll angles, or defined by three rotation angles around, for example, the z-axis, the x-axis, and again the z-axis. These rotations and the translation give us a description on how to obtain the location of the mandible with respect to its initial positioning.

These data are an essential part of our computational model of mastication. These data with six degrees of freedom allow us to describe accurately a natural movement of the mandible and, hence, the displacements of the muscles at the attachment points to the mandible. In our simulation, we seek the deformation of the muscle given a particular position of the mandible. To be able to calculate the deformation of the muscles of mastication, besides the displacements of the muscles we need a description of the material properties. The displacements and the material properties allow us to describe the underlying laws of physics by a set of partial differential equations. The solution process is based on solving these continuum-based equations of finite elasticity using a Finite Element method with cubic Hermite basis functions. These elements preserve derivative continuity across element boundaries and, when compared to linear finite elements, one can use much fewer cubic Hermite elements to achieve comparable accuracy. Additionally, the basis functions provide an efficient representation of anatomical structures in the jaw. As material properties, we use for this initial framework a simple Mooney-Rivlin type constitutive law. Mooney-Rivlin is an isotopic, elastic, rubber-like material. For more anatomically-accurate representations of the muscles, one certainly has to choose a different constitutive law. Such a constitutive law should ideally include information from different spatial scales and anatomically-accurate fibre direction.

Results

To visualize the results of our recordings, we plotted in Figure 2 the trajectory of the TMJ. For the most part this trajectory is as expected. As far as the 3 or 4 larger deviations from the main pattern in Figure 2 are concerned, we would like to refer the reader to the section "Discussion".

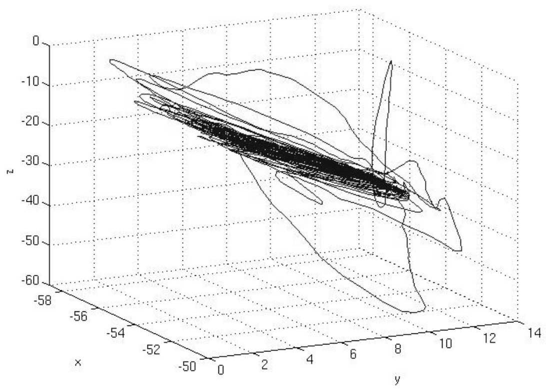

Figure 2: Trajectory of the TMJ from recordings with motion tracking systems.

Having confidence that our recordings are accurate and realistic enough for our simulations, we use the data of the first chewing cycle for our Finite Element simulation. We solve at each time step for the deformation of the muscles given a particular location of the mandible, which now is described in terms of rotations and translations from reference position. The solution at each time step gives a mathematical representation of the (large) deformations of the muscles of mastication. A kinematic model is built by solving for the deformations of the muscles given the location of the mandible at a sequence of time steps. A realistic kinematic description of a chewing process is achieved via our ability to record the location of the mandible in intervals of 0.01 seconds using the motion tracking system mentioned above. In Figures 3 to 6, we see the deformation of the masseter, the medial and lateral pterygoid, and the temporalis muscles at the beginning of the chewing cycle (Fig. 3), during the opening phase (Fig. 4), at its maximal opening during the first chewing cycle (Fig. 5), and at the end of the first chewing cycle (Fig. 6).

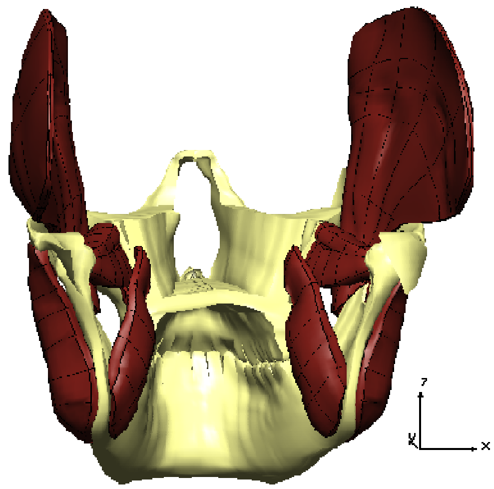

Figure 3: Muscles of mastication, the mandible and the maxilla at the beginning of the chewing cycle, t=0.00 sec.

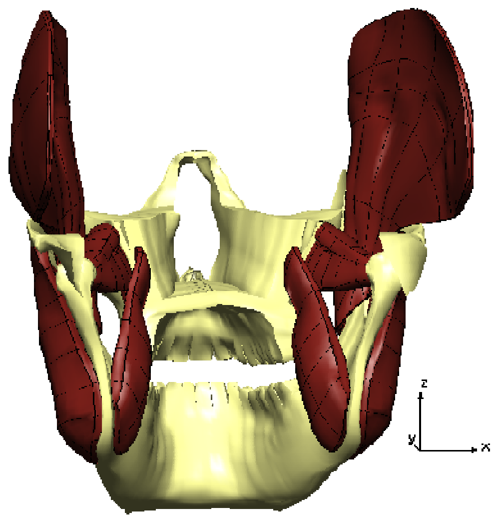

Figure 4: Muscles of mastication, the mandible and the maxilla during opening, t=0.29 seconds.

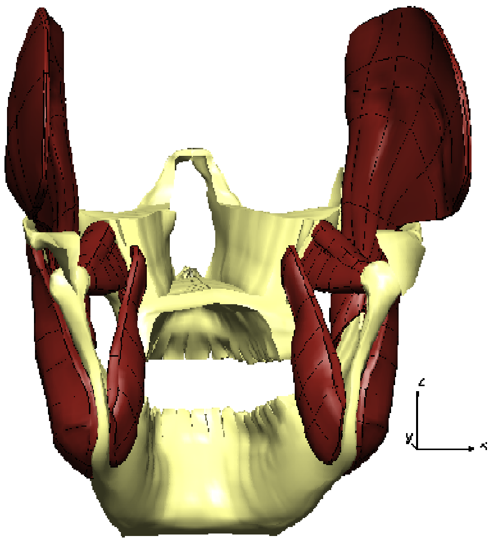

Figure 5: Muscles of mastication, the mandible and the maxilla at the maximum opening, t=0.48 seconds.

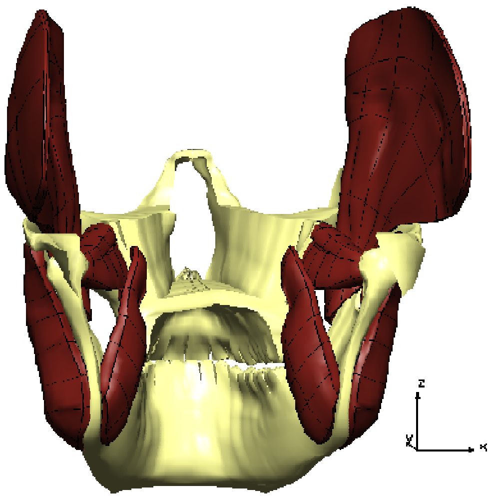

Figure 6: Muscles of mastication, the mandible and the maxilla at the end of the chewing cycle, t=1.11 seconds.

Discussion

As mentioned in the Results section, the trajectories of the TMJ look mainly as expected, but there is no doubt that there are 3 or 4 chewing cycles that do not fit into the pattern. We believe that this is most-likely due to some loosening effect of the fixation of the brace to the teeth. In further experiments, we need to eliminate such movements. Further, it appeared that the subject had to salivate more than normal during the chewing experiments. An improved design of the brace should address both issues. While the recorded data currently might not completely mimic a natural movement during chewing, it is more than sufficient for our current purpose of establishing an initial framework of simulating a few chewing cycles.

To further improve this framework, a more accurate and detailed representation of the material law for the muscles of mastication is necessary. The better our material law compares with reality, the more accurate (and hence more realistic) is our computational solution for the deformations of the muscles. It is worth noting that our current model is already capable of handling more complicated material laws, but further research is necessary to identify and validate a more accurate material law.

Conclusions

The use of a motion tracking system allowed us to collect data with six degrees of freedom. Further, we successfully transferred this data to our computational model such that we were capable of using it to describe the displacement of the muscles of mastication. We successfully applied a Finite Element method to solve the equations of finite elasticity to obtain the deformations of the muscles of mastication. In a next step, we need to improve the constitutive laws describing the material properties of the muscles. Further, if we succeed in gathering biting forces for our chewing experiments, our model could be extended to calculate muscle forces and joint reaction forces at the TMJ.

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