AN OPTICAL TRACKING SYSTEM FOR RECONSTRUCTION AND ANALYSIS OF MANDIBULAR MOVEMENTS IN REAL TIME

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Abstract - The study of the mandibular movements have received an important attention in the last few years. A number of methods have been proposed to measure mandibular movements, but none of them is ideal for recording and analyzing jaw movements in real time. In this context, this work presents a low-cost optical tracking system for reconstruction and analysis of mandibular movements in real time. The precision and accuracy obtained from the system validation were respectively 98.3 and 97.2%. The system was used to evaluate mandibular movements of 20 health subjects.

Keywords - Mandibular movements. Reconstruction Systems. Temporomandibular joint.

I. INTRODUCTION

The temporomandibular joint (TMJ) and the human mandible are part of an interesting and complex biomechanical system which is able to perform several functions and high precision movements, such as chewing, swallowing and speaking. Systems capable to record and analyze these movements received an important attention in the last few years, since they allow the diagnosis of clinical dysfunctions in the temporomandibular joints by providing quantitative parameters for this, and helps medical doctors to select the most adequate treatment plan and its future assessment [1]. For example, the maximum voluntary mouth opening can be reduced in patients with TMJ problems, as reported by Hesse et al. [2]. In fact, a reduced or excessive range of mandibular movement, as well as a defective trajectory of the jaw bone during common movements like opening-closing and chewing, could indicate signs and symptoms of TMJ dysfunction [3]. Yoon et al. [1] also reinforced the helpful capability of tools that can register and analyze condylar movements.

A number of methods, techniques and devices for recording and analyzing mandibular movements have been proposed. Unfortunately, the existent devices do not offer suitable 3D reconstruction of the mandibular movement in real time or they have prices that are not affordable to be used in common medical dental centers. The next paragraphs briefly describe some of the available methods to register and measure mandibular movements.

Hamlet et al. [4] (1997) investigated which components of mastication and swallowing were abnormal in xerostomic patients using video-fluoroscopy technique. Video-fluoroscopy technique allows visualization of the jawbone structures, but it exposes patients to ionizing.

Enciso et al. [5] (2003) and Hugger et al. (1999) describe two commercial products for the acquisition of the 3D mandibular movement that use ultrasonic sensors to acquire the trajectory of the incisive point. However, ultrasonic systems are inaccurate and extremely vulnerable to the environment conditions [6].

Yoon at al. [1] (2006) have developed a technique for recording the kinematics of the TMJ using an electromagnetic tracking device and Santos et al. [7] (2008) used a facial arc with electromagnetic sensors to measure the movement of the mandible. However, these methods are very sensitive to the existence of metal within the environment, which can limit their use for several clinical environments.

Pinheiro et al. [6] (2008) proposed a computational method for recording and analyzing mandibular movements in a two-dimensional space by using a single video camera and a reflexive marker fixed to the mandible. In this system, the camera was placed in front of the subject to record movements in a frontal plane and then it was positioned to the left (or right) side, in order to register the movements in the sagittal plane. As the system was proposed to use just one camera, it was not capable to find out the 3D trajectory of the mandible in real time.

In this context, we propose an intelligible diagnostic system of temporomandibular disorders (TMD) that can be produced with an affordable price and supports mandibular movement recording with six degrees of freedom. The system uses an optical motion capture technique that makes it capable to reconstruct, in real time, the path of strategic points of the mandible in a tridimensional space. Further than tridimensional visual information of the mandibular movements as animations, the system also provides quantitative information of position, distances, angles and velocity at any arbitral point of the model.

In order to illustrate the clinical application of the system, we conducted experiments with 20 health subjects to evaluate their mandibular movements. All subjects provided written informed consent to participate and the study was approved by the Ethical Committee of Federal University of Uberlandia.

This paper is organized as follows. In the next section, we describe the materials and methods used to develop the system. In Section III, we present the system validation methodology, which was applied to check out its precision and accuracy. In Section IV, we analyze some experimental
results and in Section V, we conclude the paper by discussing some future research.

II. MATERIAL AND METHODS

In order to realize the tridimensional reconstruction of the condylar movements, we used three infrared cameras (OptiTrack Flex V100, NaturalPoint), projected specifically for motion tracking. A camera of this type is able to identify the 2D-coordinates of an object that reflects the infrared light emitted by the camera's LEDs. In our system, we use the cameras associated with several retro-reflexive spherical markers, which were placed at key points of the subject's face. All cameras synchronously take images of the scene and reduce the image data to a set of 2D coordinates representing markers detections. This class of camera is broadly used in many applications of optical motion capture. In this study, they were set up to capture 100 frames per second.

A. Retro-reflexive Markers

Nine passive retro-reflexive markers are involved in the mandibular tracking process. Each marker has 10mm of diameter and it is covered with retro-reflexive material (Scotchlite™ High Gain Reflective Sheeting 7610, 3M). Seven of these nine markers are used for visual reference in the correspondent 3D model presented by the system's software. Some of them are also employed to support the alignment of the head and to acquire parameters of facial morphology of the subject, since facial morphology can influence condylar movements [8].

The seven markers, called secondary tracking markers, are fixed on subject's skin by using adhesive tape and a plastic support. They are positioned in the following areas: (1) ATM external surface (left and right), (2) mandible angle region (left and right), (3) on the middle region between the chin and the mandible angle points (left and right) and (4) above upper lip. These positions are illustrated in Fig. 1 (left).

In spite of the system to compute the 3D-coordinates of the secondary markers, they are not effectively used to track the jawbone. Due to the movement of the skin over the bone, 3D-coordinates of these markers do not exactly correspond to the real positions in the jawbone and skull during the movements. However, they can be used to give a roughly approximation of the facial morphology of the subject. These positions were chosen as strategic points that make possible the real time visualization of a 3D-model related to subject's face and its movements.

In addition to the seven markers mentioned before, there is a special marker, called primary tracking marker, which is really supposed to track the mandible. This primary marker is placed at the chin region and it is the only one effectively used to register the lower jawbone's trajectory.

In our experiments, we recorded mandibular movements by fixing the primary marker (also called chin-marker) in two different manners. In the first one, we used a metal marker support that was rigidly fixed to the mandible using a combination of two different dentistry materials. A thermoplastic material (godiva) was used to make the base of fixation and a zinc-enolic paste (Lyzanda®) was employed like adhesive material making the interface between teeth and the base. This support was fixed inside the mouth, between the inferior lip and the labial surface of the lower incisors. None occlusal interference with upper incisors was observed, avoiding interferences on the mandibular movements. As a result, the marker movement is correlated to the movement of the incisors and consequently to the lower jaw motion [9-10]. The marker support and its fixation position are shown in Fig. 2.

Fig. 2. The primary marker is rigidly fixed to the mandible using a metal marker support, which is attached inside the mouth, between the inferior lip and the incisors.

The method described above was employed by Pinheiro et al. [6] in their reconstruction system. In this manner, the path traveled by the chin-marker is truly related to the path traveled by the mandibular condyle. Anyway, this is little invasive method, which can cause some discomfort to the subject and consume a bit of time from the medical doctor (or specialist) during the fixing process. Because of this, we decided to conduct a parallel experiment where the primary marker is easily and quickly placed just over the skin (without the metallic support) and check out the results by comparing them with those obtained from the incisor-fixed experiments. The intention of this comparing was to figure out how much the over-chin marker trajectory and related parameters differ from those obtained when the inside-fixed marker is employed, due to displacement of the jawbone under the skin. The results suggest that the over-chin marker can track some movements with an acceptable displacement error. More details of the experiments are depicted in Section Results.

Besides the eight markers described before, a ninth marker must also be fixed to the forehead in order to estimate
its movement. In fact, mandibular movements are a combination of condylar and head movements [11]. Therefore, it is necessary to compensate head movements by using the forehead marker. Real movements of the mandible are obtained by subtracting the movement of the marker on the forehead from the movement of the marker on the chin.

**B. Camera Position**

In order to obtain the best precision, cameras were positioned according to the Fig. 3. The left and right cameras were placed about 1 meter of distance from the subject, making an angle of 60 degrees with the line connecting the person and the central camera. The central camera was put 1.3 meter from the subject and the three cameras were vertically placed about 20 cm above the head line.

![Fig. 3. Top view of the camera set-up. The left and right cameras were placed 1 meter of distance from the subject. The central camera was separated of the subject by a distance of 1.30m.](image)

These distances and positions were chosen after verifying that the cameras were able to detect all necessary markers and each detected 2D-marker looks neither too small nor too large for the cameras, which ensure good precision and accuracy in 3D reconstruction.

In order to calculate the 3D-coordinates of a point, we need that point be seen by at least two different points of view. That means it is necessary to have at least two cameras seeing that point from two different angles. Using this camera configuration, we can guarantee that all markers are seen by at least two cameras and this makes possible to reconstruct 3D-coordinates of all nine markers. Note that the central camera can see all the nine markers arranged in the face, but the left and the right cameras cannot see the markers in the opposite face side.

**C. System Calibration**

Before capturing mandibular movements, cameras need to be calibrated. After calibration, system can be used a number of times, since there is no change in camera position or in the region where capture happens.

Camera calibration is a widely used procedure in computer vision for extraction of metric information from the scene where the images will be taken. In simple terms, the process defines a mathematical correspondence between the coordinates from the image plane (given in pixels) and the real space coordinates (given in centimeters) where the movements take place [6]. Thus, the problem is to calculate some of the mathematical coefficients that permit this conversion of spaces. Direct linear transformation (DLT) algorithm is used for this purpose, because of its accuracy and flexibility in camera placement [12].

To perform the calibration, we design a calibration tool composed by a soldered stainless steel orthogonal triad with seven attached markers. Each axis of the triad measures about 25 centimeters and has a certain number of markers, whose relative positions are accurately known. The x-axis keeps three markers separated one another by a distance of 8 centimeters. Both y and z-axis have two markers separated by 12 centimeters from each other. The first marker in each axis is attached 12 centimeters from the origin and the second marker is placed 12 centimeters from the first one. As the marker’s positions in calibration tool are accurately known, it is possible to establish correspondences between 3D space and camera image planes. These correlations are used to initialize camera parameters, which make possible the 3D reconstruction.

![Fig. 4. Calibration Tool. Three markers are used in x-axis separated by 8 centimeters from each other. Two markers are used in each remaining axis (y and z).](image)

The calibration process is realized by placing the orthogonal wands where the movements should occur. In our experiments, the subjects were oriented to sit down in a chair close to the wall, so we could perform the calibration by maintaining the orthogonal triad against the wall (at the head level) for a few seconds while the program identified the markers. By considering the number and alignment of the markers on the triad, the program is able to identify the three axes automatically and to calculate the camera calibration parameters.

**D. 3D Reconstruction and Tracking**

After calibration, the system becomes ready to reconstruct mandibular movements. The image created by a camera represents a 2D projection of a 3D object. As said earlier, two such images are sufficient to yield 3D coordinates by means of photogrammetric reconstruction [12]. 3D coordinates of the right-side markers (markers at locations 1, 2 and 3 – see Fig. 1) are computed using 2D-coordinates of these markers obtained from central and right cameras. 3D coordinates of the remaining markers are calculated from images obtained from left and central cameras. All the 3D reconstructed markers are connected by a line in the 3D model so the specialist can have an approximation of the facial morphology of the subject. Fig. 5 shows a subject wearing the markers (with the chin-marker
fixed over the skin) and the respective 3D model presented by the software.

![Images of markers and camera views](image)

**2D Marker Identification**

The system expects three patterns of 2D images, according to each camera visualization. Fig. 6 depicts a sample of 2D views registered by the three cameras (left, center and right, respectively).

![Camera views of markers](image)

**3D Data Pre-Processing**

The 3D reconstructed coordinates of the nine markers were smoothed using a digital Butterworth filter with 4 poles and a cut-off frequency of 8 Hz. According to Miles [13], the mandible voluntary movements together with the tremor movements can reach a frequency of 6-7 Hz. Therefore, noise with frequency superior to 8 Hz is attenuated, giving a smoother appearance to the movement trace.

**III. SYSTEM ACCURACY AND PRECISION**

In order to evaluate our system, we perform a simple test to estimate its accuracy (agreement between the measured and reference values) and its precision (agreement among repeated measurements). The test was carried out by using a reference rigid bar of 70 mm of length with two markers attached to its extremities. The bar was moved randomly through the measurement volume and the distance between the markers was calculated for each camera frame. The estimated distance values were then compared to the known value of 70 mm. The accuracy was evaluated by determining the mean absolute error of the measured distance. We found an accuracy value of 98.3%. The precision was obtained by means of the standard deviation of those distances. The founded precision value was of 97.2%.

**IV. RESULTS**

The Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) [6] was applied to all 20 subjects involved in our experiments. The subjects were aged 18 to 25 years and, according to RDC, none of them presented signs or symptoms of temporomandibular disorders.

The subjects were instructed to sit down in a chair with the head supported by a high-density foam head support touching the occipital region of head and neck.

![Images of markers and camera views](image)
infrared cameras were used to register jawbone's movement as well as the general morphology of the subject's face.

The system accuracy and precision were estimated by performing a simple procedure, which involved moving a reference rigid bar randomly through the measurement volume and comparing the measured value of the bar with the known value of 70 mm.

The system was used to evaluate mandibular movements of 20 health subjects and the registered trajectories of the jaw were in accordance with expected patterns.

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