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Review Article

Jaw Tracking Device and Methods of Analysis of Patient's Specific TMJ Kinematics

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Abstract

The recording of the patient's jaw motion is not a new problem – history shows dentists have used various devices. The Jaw Tracking Device, developed and presented here, comprises of a computerized mechanical system instrumented with sensor technology and a man-machine interface to provide a quick, friendly and reliable setup for both doctors as well as patients. This system is used to conduct, acquire, store and analyze movement of the lower jaw as well as the temporo-mandibular joint.

Scanning models for both jaws using intraoral or stationary scanners will develop two STL meshes associated with this specific patient. The ability to display and analyze the motion of the patient's jaw presented by STL models has been extended to the area of volumetric information in form of DICOM obtained during CBCT process. Combination of STL and DICOM images driven by the same kinematics of the TMJ allows researchers to see the interaction between the internal parts of the joint without use of invasive methods under "in vivo" process and with a minimum exposure of X-ray.

Keywords: Jaw Recording; Motion Analysis; Model Scanning, STL and DICOM Images

Introduction

With the rapid development of CAD/CAM packages for dental applications, the ability to precisely measure and replicate the true motion of the lower jaw vs. the upper jaw in the virtual or real (physical) world is a significant factor in the effort to present an accurate and patient-specific depiction of Temporo Mandibular Joint (TMJ) behavior.

There are few specialty groups in dentistry where the knowledge of accurate patient TMJ kinematics is critical:

- Orthodontists
- Prosthodontics
- Implant and maxillofacial surgeons who operate on jaws
- TMJ disorder specialists
- Periodontics

Today, many dental CAD systems deal with some type of virtual design. Most of them are based on a 3D depiction of the dental work using a viewer with functions to allow the end user (dentist) to complete a project: design a crown; locate an implant; correct orthodontic occlusion, etc. This viewer, with its functions and capabilities, becomes a "quality control tool" to verify the quality of the product the dentist is about to deliver to the customer/patient. As it often happens in other industries, the quality control tool originally developed for analysis becomes a part of a closed loop control system used to improve the design (synthesis) phase of the process.

It is clear, as demonstrated by other industries, that testing of a final product can be done in different ways. One option is to test it in the real environment: fabricate a crown and try it on the real patient. The second approach is to evaluate the product in the virtual world, as far as it can be done, and only then test it on a patient.

Without the availability of the patient's true TMJ kinematics, the existing CAD/CAM developers have not incorporated lower jaw movement, resulting in a design that is inaccurate. For some applications (e.g. designing one or two crowns), the interaction between both jaws is not that critical, and it does not require knowledge about the precise trajectory of the lower jaw vs. the upper jaw. In such cases, it would be sufficient to have just one "home" or Static Occlusion.

As the virtual dental industry progresses, the demand for dental CAD/CAM programs that present the true interaction between both jaws in any position is increasing. The term used in industry for this form of articulation is Dynamic Occlusion.

The recording of the jaw motion is not a new problem. Dating back to the 1930s, there have been many of these systems. Doctors Schuyler, McCullum, and Stuart [1-3] were some of the dentists involved in this area. Dr. Stuart's mechanical system, developed in 1956, remains one of the more accurate manual recording and replication systems available today.

This system with a fully adjustable manual articulator was the state of the art in dentistry and widely used for the last 50 years. In spite of many successful dental cases restored using this technique, the mechanical system could not find acceptance on the broad market due to:

- The complexity of the system
- Interpretation and use of results
- The heavy requirements for training
- The duration of the setup and recording process
- Lack of interface to the computer

To overcome these problems, GnathTech has developed a computer-based recording system (The Digital Recorder [4], which produces the recording information for a patient in less than 25 minutes (including setup). This information is stored and can be applied to a variety of tasks in dentistry when a modern dental CAD/CAM program is used. The information can be interfaced to any computer package and will replicate the true interaction between the patient's jaws.

To provide more sophisticated dental services using restorative and prosthetic devices, future devices are expected to be designed and fabricated with improved function related to jaw movements. The analysis of multiple-axis mandible movements for the purpose of recovering oral function of patients has already been widely investigated in prosthodontics. However, at the moment, CAD software only establishes static morphological reproduction of crowns and FPDs. Production of dynamic occlusal morphology of CAD process is still challenging but must be made practical in the near future [5].

Digital Recorder/Jaw Tracking Device

GnathTech TMJ Digital Recording system allows the dentist to record and preserve the real time trajectory of the lower jaw movement. These movements are specific to each patient and based on the geometry and morphology of the patient's TMJ. This information can be used to drive two GnathTech articulators to perform the Dynamic Occlusion: a virtual (on the screen) as well as a "real" physical (Electro-mechanical) one moved by a set of servo-controlled motors and suspension. These two articulators can be driven in a Play Back mode through the entire record or any part of it in the same time scale as they were recorded or at any other speed.

The Digital Recorder developed by GnathTech comprises of a computerized mechanical system instrumented with sensor technology and a man-machine interface to provide a quick, friendly and reliable setup for both doctors as well as patients. This system is used to conduct, acquire, store and analyze movement of the lower jaw as well as the temporo mandibular joint.

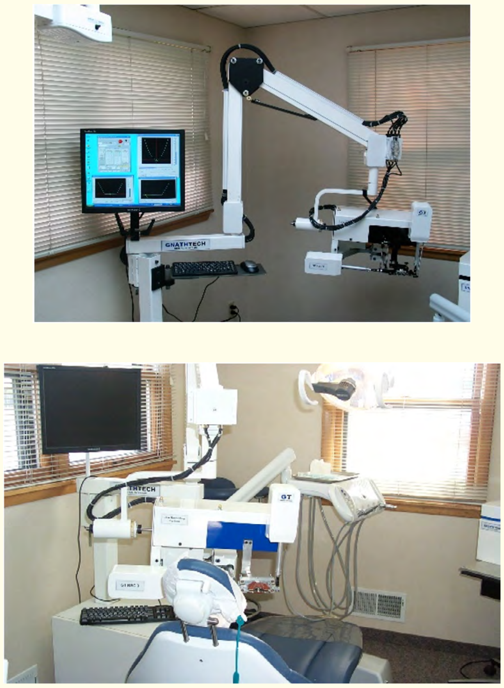

Figure 1

The Recorder's sensor system is attached to the patient's upper and lower jaws through a system known in dentistry as "clutches". The technology of clutches has existed for years, and it is used through the dental industry. Industry standard clutches were used for this Recorder, but it is not limited to the use of only these clutches.

Mechanically, the system consists of the following major components.

Suspension system

With a 4DOF Articulated Arm used in the process of a patient's setup of the recording session and a 3DOF wrist mounted at the end of this arm. This 7 DOF articulated mechanism with its high dexterity provides the needed flexibility to achieve a completely balanced suspension of the Sensor Frame attached to the patient's upper jaw. In combination with the use of frictionless joints through the entire suspension system, this mechanism delivers not only balanced but also force neutral conditions for the interface between the patient and the recording system.

Sensor Frame

Head rigidly attached to the last DOF of the wrist and containing a Sensor cluster instrumented with Displacement Feedback Sensors to monitor the movement of the Main Lower Jaw Recording Bar.

Sensor-Patient interface system with:

- Main Lower Jaw Recording Bar attached to the sensor cluster system on the sensor side and to the Lower Jaw Clutch on the patient side.
- Upper Jaw Clutch system mounted on the Sensor Frame and interfaced to the Upper Jaw through a clutch.
- A Release Mechanism to connect/disconnect the Sensor Cluster to/from the patient's clutch system and to allow the Lower Jaw to obtain/restrain its natural DOF and motion.

Electronics

The Recorder includes a set of sensors attached to the moving Main Recording Bar. To sustain a repeatable and accurate recording in real time a system of high-speed data acquisition channels is used to condition, read in and store the information simultaneously from all sensors [6]. Two digital I/O channels are used to allow the dentist to control the process of recording in "hand free" mode through two foot-operated pedals. Those pedals are used to signal the computer system when to "arm" the system, and to start and stop the recording.

Coordinate systems

The recorder represents a combination of a multi-degree of freedom mechanical system with a network of monitoring sensors. The information from those sensors cannot be used directly for TMJ motion analysis. This information must be converted into something meaningful such as a trajectory of the TMJ's condyles, or motion of the lower jaw, before it can be understood and interpreted by the practicing dentist or used within a CAD/CAM system. To achieve that a set of coordinate systems rigidly connected to and associated with key parts of the recorder has been established. It is also important to determine all major sets of parameters (called domains) for each coordinate system. Those major domains are:

- TMJ domain, associated with coordinates of each center of the condyles and the rotational angle around the centerline between those (left and right side) condyles.
- Sensor domain, consisting of 9 sensors, and can be considered a 9 DOF domain. There is a cross-coupling relationship between those 9 parameters to provide only 6 independent DOF information for the position of the Main Recording Bar.
- Joint Domain, representing all mechanical joints used in the recorder system as a part of a multi-DOF linkage. This domain has been broken into 4 sub domains: 3 subdomains associated with each sensor cluster and the 4th domain associated with suspension system.
- Lower Jaw clutch/transfer bar World Domain reflecting the World DOF of the Jaw measured relative to the reference or Home coordinate system. This domain with its coordinate system is rigidly attached to the Main Recording Bar (or Lower Transfer Bar, which is just a simple offset away from the Main Recording Bar) has 6 parameters (6 DOF): three translational DOF: X, Y and Z of the center of the transfer bar and three rotational: Pitch, Roll and Yaw.

Direct and Inverse Kinematics

When the lower jaw, attached through the clutch system to the transfer bar and Main Recording Bar, moves in World Domain it forces the Main Recording Bar to change the readings from all sensors in Sensor Domain. Those readings (called Feedbacks) are sent to the computer system for processing. The processing in this case means converting information from the Sensor Domain into the Jaw Domain. This transformation requires the establishment of a kinematics model for the entire system using coordinate systems associated with each individual DOF. There are two major kinematics transformations that should be recognized here: Direct Kinematics Transformation (DKT) and Inverse Kinematics Transformation (IKT). Both transformations represent a procedure to convert known information from one domain into information of the other domain. The DKT is performed when the World parameters of the Jaw are known or given. This transformation would convert it into Sensor Domain information [7]. The IKT is used when the information from all sensors is given (in form of feedback information) and the position of the jaw in World Domain needs to be obtained.

DKT is always unique and relatively fast. The IKT is more complicated and since Gnath Tech uses an over-constrained sensor domain (number of DOF in sensor domain is greater than 6) a DLSM method to determine the optimal solution for the World Domain has been applied [8]. The use of over-constrained/redundant sensor system increases the accuracy and repeatability of the conversion process going from Sensor Domain into the World Domain. Use of direct and inverse Jacobian matrix allows it to perform both transformations at very high sampling rate in the real time application such as recording.

The user interface includes the screen-oriented control panels which allow the dentist or a trained technician to conduct the recording process as well as to display the immediate results of TMJ movement. Two foot-operated pedals control the process of starting and stopping recording.

Modes of recording

After setup is completed, and the patient's jaws are secured through a clutch system to their transfer bars, the recording process can be started. At this "home" or reference position the release mechanism disengages the lower clutch system from a stationary upper clutch system. The patient's mandible becomes free of any unnatural constraints. It can be moved relative to the maxilla in normal manner.

Hinge Movement is the first step in the recording process - the determination of the hinge axis. This axis represents an imaginary, but very critical, line between the geometric centers of the left and right condyles of the TMJ. As it is known from dentistry, during the first 15 mm of mouth opening, the TMJ performs an almost pure rotation motion around the axis, which is functioning at this point as an instant TMJ's hinge. This program determines the location of those center points CndlLeft and CndlRight in the "jaw" or Lower Jaw Transfer bar coordinate system. Border movement to the right. During this movement, the recorder monitors and stores the trajectory of both previously obtained central point's CndlLeft and CndlRight as well as angle of rotation of the jaw around the hinge axis. Border movement to the left. This movement is similar to the previous move. And the last movement is called Protrusive motion when the jaw is moved forward.

Those four border movements are typical for a traditional recording process used by dental profession for many years. But the GnathTech Digital Recorder is not limited to those four motions. It can be used for recording of any arbitrary jaw movement within the physiological constraints of the jaw including chewing processes or any other movement within the borders.

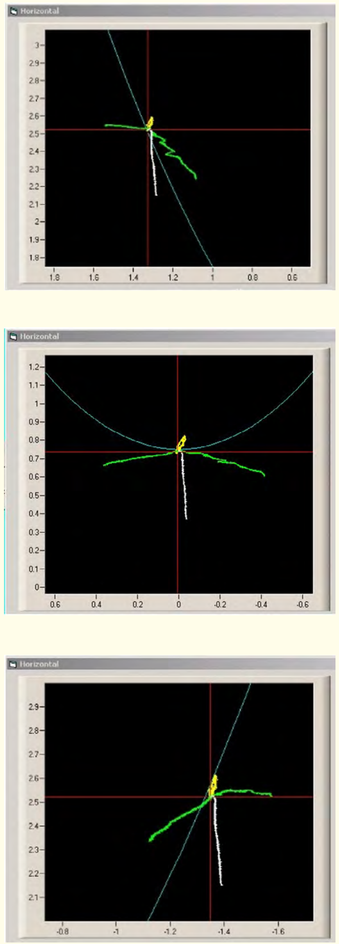

Figure 2

Results are stored in the form of multi DOF time history files. Any cross section of this multi-DOF data structure represents all information about the position and orientation of the Jaw with its condyle center points in 3D space at that time.

Those results can be used in "play back" process to analyze the trajectory on point-by-point basis for any time instance. This file can be transferred to another existing Dental or mechanical CAD to interface this motion information as a plug-in with other related applications. This information also can be used to set up any existing manual adjustable mechanical articulator as well as to drive a GnathTech fully automated computer controlled Electro-Mechanical Articulator [9] or depicted and analyzed with GnathTech Virtual Articulation for Dynamic Occlusion (VADO) on the screen.

Performance

The Digital Recorder has a 1-micron resolution in the Sensor Domain for each individual data acquisition channel. Trajectory accuracy is about 1.5 microns. Mandible DOF accuracy (including the accuracy of kinematics transformation) is better than 4 microns. Since the digital nature of the recorder, the data collection during the recording process is controlled electronically by a programmable triggering source. The frequency of the source determines the density or number of so-called "key points" on the trajectory. This density of recorded points on the trajectory is a part of a setup file with default value at about 400 points/ 1mm, so in the default case, the points are spread about 2.5 microns apart.

It has been a known challenge in dentistry for a long time: to develop an accurate, repeatable, and reliable device to duplicate existing or produce any arbitrary realistic jaw movement. During this replication a set of casts: one for each jaw should be made to represent the patient's specific jaws. As discussed above, it can be done in the virtual world in the form of Virtual Occlusion, or in the real environment on a mechanical (physical) articulator.

Virtual Articulator

As it has been done in the past, the results from the process of recording the patient's TMJ kinematics are presented as a series of plane pictures to track the position and motion of the jaw. In fact, those results need to be interpreted by an experienced dentist before they can be applied. It is important to note that the results of recording, particularly in the case of recording of border movements, do not show, and do not include, any interaction of the teeth. The lower jaw moves relative to the upper jaw without performing any occlusal interaction to exclude its influence on TMJ kinematics.

Dynamic Occlusion

Virtual Articulation Engine first developed to control an electro-mechanical articulator has become a foundation for a Dynamic Occlusion Package to be used in Digital Dentistry. This Virtual Articulator can be used to simulate any existing mechanical semi-adjustable and fully adjustable articulator. (Never the less, the best results are achieved by combining the Virtual Articulator with a "true" recording information obtained from the Jaw Tracking system to simulate specific patient's jaw motion without any compromise and approximations).

The virtual occlusion or Virtual Quality control testing cannot be performed without obtaining one more piece of specific patient's information: Digital images of both jaws (in the form of STL [11] for surface analysis or DICOM [10,12] for volumetric study).

Figure 3

This leads to another step in the development of the dental CAD that can be called a "virtual" model. It is common practice in dentistry that a pair of casts for the upper and lower jaws are fabricated to preserve the shape and relative position of both jaws. Digitizing the jaw casts with a surface scanner enables the dentist to obtain a 3D representation of the real surfaces. The scanning device today is capable of digitizing the surface with high accuracy (20 microns or better) and preserving it in the form of data files with STL format.

Digital imaging (STL)

Surface Scanning allows us to bring in and display the TMJ with its upper and lower jaws on the screen. That is the first step in the creation of a Virtual Articulator. It requires a device with high resolution, accuracy and speed. Otherwise, this process is not practical.

It is critical at this point to provide a matrix of coordinate transformation, which is used later on during the virtual modeling for proper positioning of models on the screen. Scanning of a jaw's cast individually on the fixture (which can maintain the integrity and association between both jaws in its reference coordinate system) enables us to obtain their digital representation and store it for future display and analysis. GnathTech has designed a set of fixtures to be used during the scanning, to place the digital image of the casts at their proper position on the screen relative to the TMJ hinge.

Home or Static Occlusion

Use of fixtures and procedures provides the proper orientation between both casts at what it can be called as a zero or home occlusion. This technique has been expanded by a graphic rendering tool to depict both surfaces at any relative position based on the information obtained from the recording process.

To achieve a realistic and natural depiction of the motion on the screen, the lower jaw model/surface is moved based on the recording information. During this articulation, the dentist can observe and analyze a true interaction between the teeth of both jaws and make an appropriate design change. The depiction and analysis described above can be called a "surface-based occlusion" since the interaction takes place only between surfaces obtained from surface scanning for both casts.

Digital Imaging (DICOM)

The ability to display and analyze the motion of the patient's jaw has been extended to the area of volumetric information by combining an STL images for the cast's models obtained from the "surface" scanners with a DICOM images if the entire jaw (including condyle and fossa areas) obtained during CBCT process [13]. A "fusing" process to combine both worlds together has been developed.

Volumetric scanning

Manipulating the images of the Virtual cast models on the screen; we are dealing with the digital representation of the casts, more precisely with its surface images or mesh images. That means actually that we don't know much about anything inside the model or under the "skin". To look "deeper" a CT scans technology known to covers many different test/procedures such as scanning parts of the body can be used. It is based on new Cone Beam technology and called CBCT. Usually, it is a relatively small device designed with particular interest for dentistry, very fast (takes about 20 secs. per scan) and it is less harmful for the environment and patient (1/17 of a regular CT dosage of X-ray radiation).

To extend the surface scanning process to volumetric models obtained from CBCT scans the following steps are required:

1. Perform a single CBCT scan to obtain the volumetric information for upper and lower jaws including the area surrounding TMJ (fossa and condyles). This scan should be done in the "centric relation" using a splint to separate the teeth.
2. Separate the DICOM volumetric information into two parts:
   i. DICOM file which contains only cranial volumetric information with specific details for fossa on both sides;
   ii. DICOM file which contains only volumetric information for the mandible, including both condyles.
3. Convert these two separated images of cranial and mandible into STL format.

In steps 2 and 3, the DICOM information is separated into two images and converted into the STL format using digital imaging software such as "Create Model" [14].

As mentioned above, during the scanning, the patient wears a centric relation splint to separate the teeth so the images for both jaws can be identified and preserved in two separate files.

Fusing STL and DICOM images

During this process, the two images obtained from the CBCT scans and converted to the STL format should be fused/mated with the corresponding STL image of the models obtained during a surface scanning of casts. Using a set of simple fixtures and "similar" features shared between the corresponding parts, it can be considered as a superimposing process by which the mesh of the lower cast is laid over the image of the mandible obtained from the CT scan as well as the upper jaw laid over the maxilla area of the cranial image.

Combine Virtual Articulation

Articulation of these two models after the "fusion" is no different than articulation of just two casts obtained from the original surface scanning. The computer depicts the entire extended images the same way as the original images by driving them through the recorded movements. In this case we can see the interaction not only between teeth but also the kinematics between condyles and fossa in the TMJ area.

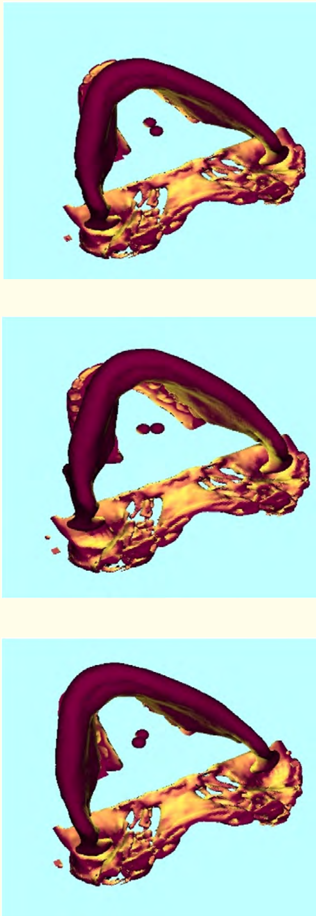

Figure 4

Conclusion

GT Virtual Articulation package is developed on principals of an open architecture system. It allows any new/progressive ideas for Dental Tooth Contact Analysis (DTCA) in the areas of graphic representation, analysis and as well as for any standard engineering packages (such as FEA) to be interfaced with as a plug-in module.

The package can be used as a stand-alone system interfaced to the existing Dental CAD/CAM packages through a file system and be used as a QC digital tool box or can be integrated into a CAD to take the full advantage of its analysis capability during the dental design step to reduce a number of iterations to develop the best dental work.

Combination of STL and DICOM images driven by the same kinematics of the TMJ allows researchers to see the interaction between the internal parts of the joint without use of invasive methods under "in vivo" process and with a minimum exposure of X-ray.

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