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Using a Motion-Capture System to Record Dynamic Articulation for Application in CAD/CAM Software

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Abstract

Purpose: One of the current limitations of computer software programs for the virtual articulation of the opposing teeth is the static nature of the intercuspal position. Currently, software programs cannot identify eccentric occlusal contacts during masticatory cyclic movements of the mandible.
Materials and Methods: Chewing trajectories with six degrees of freedom (DOF) were recorded and imposed on a computer model of one subject's maxillary and mandibular teeth. The computer model was generated from a set of high-resolution μ-CT images. To obtain natural chewing trajectories with six DOF, an optoelectronic motion-capturing system (VICON MX) was used. For this purpose, a special mandibular motion-tracking appliance was developed for this subject.
Results: Mandibular movements while chewing elastic and plastic food samples were recorded and reproduced with the computer model. Examples of mandibular movements at intraoral points are presented for elastic and plastic food samples. The potential of such a kinematic computer model to analyze the dynamic nature of an occlusion was demonstrated by investigating the interaction of the second molars and the direction of the biting force during a chewing cycle.
Conclusions: The article described a methodology that measured mandibular movements during mastication for one subject. This produced kinematic input to 3D computer modeling for the production of a virtual dynamic articulation that is suitable for incorporation into dental CAD/CAM software.

Clinicians and dental laboratory technicians, provided with information from intraoral scans, impressions, or from working casts, can now manufacture intra- and extracoronal tooth restorations remotely from dental patients using computer-aided design/computer-aided manufacturing (CAD/CAM) systems. The advent of CAD/CAM systems for fabricating dental restorations has resulted in the development of proprietary software that provides virtual articulation of opposing teeth. Current systems only satisfy static intercuspal position and do not account for dynamic masticatory relationships, including eccentric occlusal contacts. So far, most behavioral chewing studies have relied on a 2D articulograph.[1-3] These devices were originally designed to measure movements of the tongue and mouth for speech research. Although 3D articulographs are now available, they have not been used to track mandibular masticatory movements. Previous reports on computer modeling of occlusal surfaces of posterior teeth using virtual articulation in a CAD/CAM system have based their measurements on a computer-generated occlusal path or a head-related 3D registration system that would interfere with mastication.[4] Therefore, there is a need for a method that can accurately measure the masticatory cyclic movements of the mandible and evaluate the interaction between teeth by imposing the measured chewing trajectories onto a 3D computer model.

Extensive research focusing on developing algorithms for representing and visualizing 3D models of teeth, as well as tracking the motion of mandibular movement, exists. 3D models of single teeth, dentitions, occlusion, or entire jaws are obtained by either acquiring sets of 2D images and using (automatic) segmentation algorithms or by surface scanning.

The most common imaging techniques have been based on mechanical contact,[5] laser scanners,[6-9] intraoral video cameras,[10] "cone-beam" computed tomography (CT),[11,12] or μ-CT imaging.[13-15]

Recording mandibular movements dates back over 100 years. The first mandibular tracking devices used photographic imaging techniques that followed the traces of "light-reflecting" markers on a facebow.[16-18] After experimenting with photographic and roentgenographic (X-ray-based imaging) methods, magnetic and optoelectronic techniques have emerged as the most applicable techniques. The Case Gnathic Replicator, developed by Messerman and Gibbs at Case Western University in 1969,[19] was one of the first electronic systems to record and play back accurate 3D jaw movements.[20] In 1974, Lewin and coworkers described a magnetic recording system[21,22] that formed the basis for more clinically applicable and commercially available magnetic tracking systems such as the Sirognathograph Analyzing System[23,24] by Maruyama and coworkers or the 2D and 3D articulographs from Carstens Medizinelektronik (Lenglern, Germany).[1-3,25] Although optoelectronic capturing systems have mainly been developed for tracking human movement (gait),[26] they have previously been used or customized to record mandibular movement, for example, the Selspot, Selcom AB, by Karlsson in 1977[27] (Gothenburg, Sweden) or the JAWS-3D system by Mesqui and coworkers in 1985.[28-30]

None of the mandibular motion-tracking systems have, however, been specifically developed for measuring natural chewing trajectories with six degrees of freedom (DOF). To fully describe the movement of an object in three dimensions, six DOF are needed: specifically three rotations and three translations along three perpendicular axes. The fixation of the markers for systems focusing on functional aspects of the masticatory system may significantly interfere with natural chewing behavior, for example, the metal splints used in Mesqui and Palla's[28] system for investigating temporomandibular joint (TMJ) disorders.[31,32] Food and nutrition scientists have traditionally been interested in overall chewing characteristics, such as the number of chewing cycles, chewing frequency, or maximal opening while chewing particular food samples, and therefore prefer to use simpler 2D measuring methods.[1-3,25,33-35]

This article describes the design of a simple dental appliance that can be used within an optoelectronic motion-capturing environment to record natural chewing trajectories in six DOF. It will also describe how such trajectories can be translated onto an accurate patient-specific 3D geometric model, created from high-resolution images. The combination of visualization and motion-capturing techniques to obtain dynamic descriptions of natural chewing opens new opportunities in prosthetic dentistry for diagnosis and treatment planning and educational applications.

Materials and methods

The proposed method is based on a geometrical model of a subject's maxillary and mandibular teeth, generated from a set of μ-CT images using an automatic segmentation algorithm, and recordings of chewing trajectories obtained from an optoelectronic motion-tracking system. The specific motion-capturing system used in this study is the VICON MX system located at the Biomechanics Laboratory, Department of Sports and Exercise Science, University of Auckland, Tamaki Campus. It should be noted that most other imaging methods[7,9-11] or other optical motion-capturing systems, which are commonly used for human movement and gait analysis,[26,36-38] could be used in a similar way. Such gait analysis systems are quite widespread and accessible. The geometric and kinematic data were derived from a 32-year-old man, fully dentate, with normal dentition. The patient presented with an edge-to-edge occlusion between the maxillary and mandibular left central incisors (No. 9 and 24) and the maxillary and mandibular lateral incisors (No. 10 and 23). The subject had prior orthodontic treatment at the age of 10 and was free of TMJ symptoms.

Creation of patient-specific models of the maxillary and mandibular teeth in occlusion

To combine dynamic chewing trajectories with accurate subject-specific geometric models, it was assumed that the maxillary teeth were stationary and that the movements of the mandibular teeth were described with respect to a reference position (mandibular teeth in occlusion). A Skyscan 1172 μ-CT scanner was used to acquire two separate sets of high-resolution images from dental stone casts of the subject's maxillary and mandibular teeth. The voxel resolution of the images was 34.65 μm. Based on these two sets of images, an automatic segmentation algorithm was used to generate a geometrical model of the surfaces of the maxillary and mandibular teeth. The voxel color of the reconstructed μ-CT image slices was related to the average density of the respective voxel of the scanned object. The significantly different densities of dental stone and air were therefore represented on the μ-CT image using colors at opposite ends of the spectrum. The change in color between the dental stone and air provided input to a volume-rendering algorithm, capable of automatically reconstructing the surfaces (magnitude of the color gradient exceeded a certain threshold value) of the dental casts.

To achieve occlusion, the dental stone casts were, before scanning, rigidly fixed in occlusion by gluing two differently oriented pins across the two casts. After clipping the pins and separately scanning the maxillary and mandibular teeth, the pins were reconstructed using the same segmentation process as for the geometrical models of the maxillary and mandibular teeth. Realigning the reconstructed pins provided an easy and straightforward mechanism to occlude the maxillary and mandibular casts.

Manufacture of a mandibular motion-tracking appliance

The key to investigating the significance of shape and form of teeth in function during mastication was to accurately record mandibular movements while chewing food samples. For this purpose, a special mandibular motion-tracking appliance for an optoelectronic motion-capturing system was developed. The basic methodology behind optoelectronic tracking systems is that high-speed cameras capture the location of light-reflecting markers and determine the location of their centers in space. Tracking mandibular movements is reduced to the task of how rigidly such markers are fixed to the mandible, even while chewing hard foods.

The mandibular tracking appliance was manufactured by first making primary alginate impressions (Aroma Fine DF III, GC Corporation, Tokyo, Japan) of the subject's maxillary and mandibular dental arches using stock trays. Primary casts were poured in dental stone (Quickstone Laboratory Stone, Whip Mix, Louisville, KY). Custom impression trays were constructed in light-cured polymethylmethacrylate (PMMA) (Megatray, Megadenta Dentalprodukte GmbH, Radeberg, Germany). Secondary impressions were made with the same alginate impression material and poured immediately in vacuum-mixed dental stone. This produced working casts on which the appliance was designed and constructed. The maxillary and mandibular casts were positioned in centric occlusion to identify areas where wire retention clasps could be placed through the occlusion so as not to interfere with the centric and eccentric mandibular chewing cycles of the mandible during function. Two 0.7-mm gauge stainless steel wire (Remanium spring hard, Dentaurum, Pforzheim, Germany) "Adams" clasps were fabricated on the left and right mandibular second premolars to provide anterior retention and stability. Two 0.8-mm gauge stainless steel wire "Ball" clasps (Remanium ball retention clasps, Dentaurum) were placed between the left and right mandibular first and second molars to provide posterior retention and stability. A lingual base plate was constructed in self-curing PMMA (Orthocryl, Dentaurum) to link the clasps. This provided a retentive, stable appliance to which the labial arch supporting the tracking indicators could be soldered via the cross bars of the Adams clasps. The subject's lip line in relation to the maxillary central incisors was identified, measured, and transferred to the maxillary cast. The casts were occluded with the mandibular appliance in place. A labial bow in 1.0-mm gauge stainless steel wire (Remanium spring hard) was constructed and soldered (Universal Solder, Produits Dentaires SA, Vevey, Switzerland) to the bridge of the Adams clasps so as to project through the lips, while not interfering with the lower lip during function and in centric occlusion. An extraoral cross arch bar in 1.0-mm gauge stainless steel wire was constructed and soldered in the horizontal plane to which the reflective tracking balls were attached (Fig 1). The appliance weighed 7.92 g, including the reflecting markers.

Experimental set up for motion-capturing session

The motion-capture system consisted of the subject sitting comfortably upright, eight interconnected high-speed 4-megapixel digital cameras, which processed full-frame resolutions up to 370 frames per second, a total of six light-reflecting markers, and VICON's hardware and software analysis system. The cameras were evenly distributed around a half circle at a distance of about 3 m in front of the subject. This half-circle setup was chosen to ensure that at any given point in time, each marker was in the viewing field of at least two cameras. Out of the six relevant markers necessary to capture mandibular movement, three markers were placed on the bridge of the nose and two on the forehead, where skin movement during mastication was believed to be minimal. The remaining markers were fixed to the custom-made appliance (Fig 1). The three markers on the head were sufficient to eliminate the subject's head movements.[27]

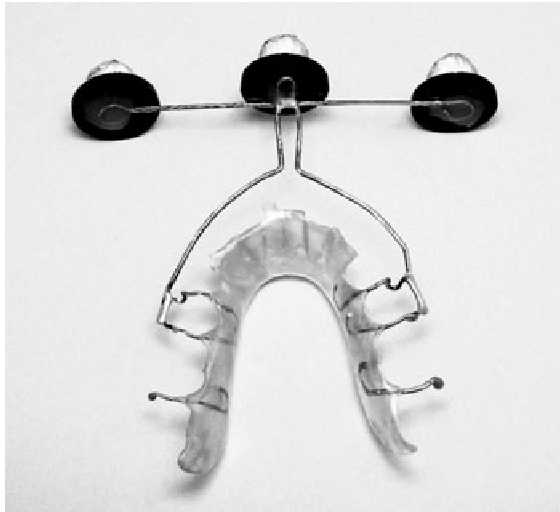

Figure 1 Design of the custom-made appliance with three light-reflecting markers (on the top of the picture) used to track mandibular movements with the motion-tracking system VICON MX.

Collection of jaw movement data during chewing of edible model foods

Before commencement of the recording, the motion-capture system was calibrated using VICON's recommended static and dynamic calibration test. Furthermore, to accustom the subject to the instrumentation and procedure, the subject wore the appliance for 15 minutes and chewed some of the same food samples that were to be used for the actual recording. The subject was seated comfortably, and a food sample was placed on the subject's tongue. The subject was instructed to bring his teeth into occlusion and remain in that position until signaled to start chewing (beginning of the recordings). The subject then placed the food between the teeth and completely chewed the sample until swallowing, at which point recordings were stopped.[1,2] The collection of the chewing data involved two food samples, one showing elastic (E, gummy bear-like) and the other showing plastic (P, caramel-like) rheological behavior. The food samples were 20 mm in diameter and 10 mm in height. The mechanical hardness and rheological properties of the samples were comparable in hardness to the food samples E_4 and P_3 used in the previous work.[1] The subject gave informed consent after receiving a full explanation of the goals and evolution of the study.

Analyzing the raw motion-tracking data

A data format that listed the location of the three markers on the appliance and the three markers on the forehead and the bridge of the nose was chosen as the output format. During a postprocessing step, the recorded data, which described the coordinate positions of the markers within the rectangular coordinate system chosen by the motion-tracking analyzing software, were linked to the movements of the mandible.

For this study, a single global coordinate system was used to analyze and visualize the mandibular movements during the chewing experiments. The relative marker positions of the appliance were determined with respect to the mandibular teeth during a separate registration process using a multiple axis articulated measuring arm with six DOF. The plane spanned by the location of the appliance markers in occlusion was chosen as the reference plane. It was assumed that the distances between the markers remained constant over time. The recording of six marker positions at a sequence of time steps was thought to be sufficient to uniquely determine the motion of the head and mandible in three dimensions.

The derivation of the mathematical description of the kinematics of mandibular movement was broken into three parts for each time step. First, the head markers determined the movement of the head at that particular time step; second, the "absolute" movement of the markers on the appliance was calculated by subtracting the respective head movement; last, the appropriate rotations and translations (the rigid body motions) were calculated to describe the mapping of the reference marker positions on the appliance (marker positions of the first time step in occlusion) to current marker positions (corrected by the head movement). The same rigid body motions were then imposed on the geometrical model of the mandibular teeth.

It is well known that recordings of motion-tracking systems contain noise. Without the knowledge or awareness of the user, data are often directly filtered by the software of the motion-tracking system. In this study, the unfiltered and raw data were retrieved. To help remove noise in our recordings, a simple "smoothing" procedure that substituted the current location with the average value of its seven (temporal) neighboring locations was employed. To prevent over- or undersmoothing, the degree of smoothing can be adjusted by repeating the averaging procedure. This smoothing procedure was repeated three times for all data presented within this article.

Results

The results of recording natural chewing trajectories using the method described earlier are depicted in Figures 2 to 5. These figures represent one set of chewing data for a plastic food sample (Fig 2) and one set of chewing data for an elastic food sample (Figs 3 to 5) from a single recording session. During that particular recording session, a total of 10 food samples (five elastic, five plastic) were chewed. Figure 2 shows the 3D movements and the velocity of a virtual point in between the two mandibular incisors (interincisal point), with each quantity presented as a function of time while chewing a plastic food sample. Figures 3 and 4 depict displacement–displacement curves of the mandibular interincisal point in the frontal (A) and lateral views (B), while chewing the elastic food sample. The lateral–medial, anterior–posterior, and superior–inferior displacements of Figure 2 were calculated as described earlier. The velocities were determined by calculating the shortest distance between the 3D locations of markers on consecutive time steps and were divided by the respective time interval. In mastication studies, graphs such as the ones depicted in Figure 2, in particular 2A and 2C, form the basis of investigation and are used to analyze the data for variations in lateral–medial and superior–inferior jaw movements and opening and closing velocities with respect to changes in, for example, age, dental status, or food properties.[1–3,25,39] However, such analysis has predominantly been based on data from 2D measurements. Figures 2 to 4 are in agreement with previously published works[19,22] and provide a (weak) validation that the proposed way of computing the mandibular movement was capable of recording and computing natural chewing trajectories.

The visualization of mandibular movement is often limited to time-displacement or displacement–displacement plots within a particular plane; however, geometrical representations of the upper and lower teeth allowed evaluation of the full data set. Such geometrical models can be loaded into interactive visualization programs and, hence, can be viewed from different angles and viewpoints. The visualization program used in this study was CMGUI (http://www.cmiss.org/cmgui), an open-source software project led by the Bioengineering Institute at the University of Auckland. In addition to the standalone software package, CMGUI, a Mozilla Firefox plugin, ZINC (http://www.cmiss.org/cmgui/zinc) that provides an interactive viewing tool for web applications exists.

Further, the models can be animated and enhanced by displaying chewing trajectories at desired intraoral locations. This combination of geometrical models and 3D chewing trajectories provided enhanced insight into mastication. For example, the local derivative (slope) of the chewing trajectory at any given point during the cycle can be considered as the resulting force that caused the mandible to be displaced in a particular direction. The direction of this force can also be interpreted as the direction of the biting force. Hence, the slope of the chewing trajectory, as depicted for a particular instance by the red arrow in Figure 4B, can provide more in-depth information on mastication, as well as subject-specific masticatory habits of crushing, grinding, and shearing food (Fig 5). Such information can provide additional guidance in the design process of dental implants, crowns, or fixed partial dentures. Furthermore, such a method can also be used effectively in the provision of dental restorations as a dynamic virtual articulator to identify eccentric premature occlusal contacts during mastication.

Discussion

A successful method for recording jaw movement must not inhibit or interfere with natural chewing. Recording devices cannot move with respect to the mandible, even while chewing hard foods, nor create any discomfort for the participants, nor alter normal salivation. This appliance was specifically created for this subject and was designed with an emphasis on not obstructing the occluding surfaces. It was also lightweight and was made from specialized dental materials that minimized the stimulation of salivation beyond what would occur naturally. On questioning the subject at the completion of the experiments, the subject did not report any subjective increase in salivation from wearing the appliance. The subject did, however, mention that the plastic food had a tendency to stick to the teeth (and to the appliance) towards the end of the chewing sequence. The tendency to stick to the teeth could be a sign that the acrylic resin material of the appliance might have had an influence on control of the food bolus and, hence, might have influenced the chewing

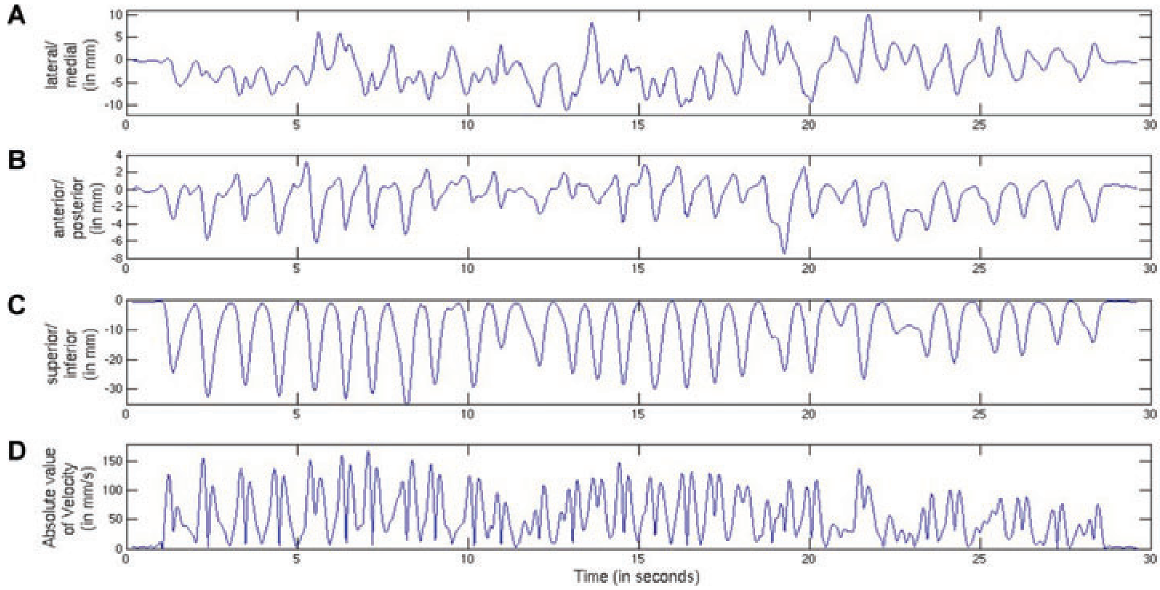

Figure 2 Experimental data for a plastic test food sample. Depicted are the displacements of the interincisal point on the mandible in each dimension (A–C), as well as the absolute value of the velocity (D).

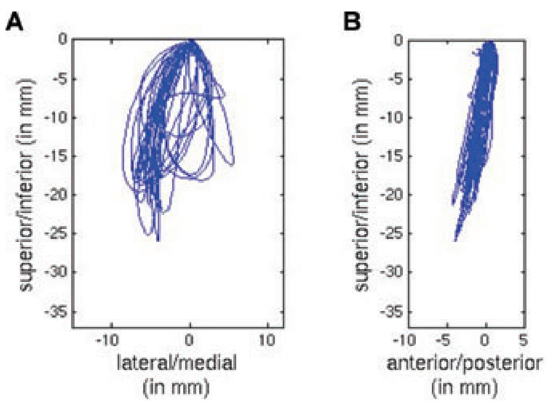

Figure 3 Displacement–displacement curves of the interincisal point on the mandible in the frontal (A) and lateral view (B) while chewing an elastic food sample.

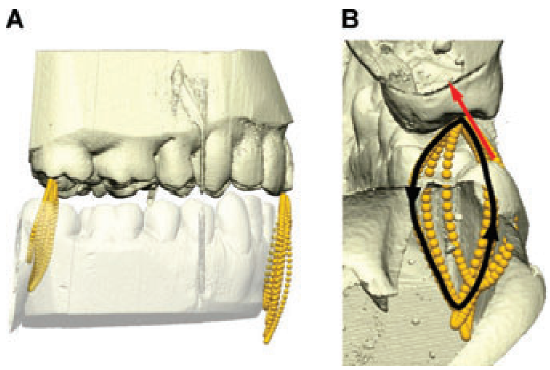

Figure 4 (A) Mandibular right second molar and central incisor trajectory for the first three chewing cycles with the elastic food sample depicted in Figure 3. (B) Mandibular right second molar trajectory (black) with the arrow (red) depicting the direction of the movement of the molar close to the end of the first chewing cycle.

Figure 5 Sequence of mandibular and maxillary right molars at the end of the first and beginning of the second chewing cycle with an elastic food sample (t = 0.73 second (1); t = 0.80 second (2); t = 0.85 second (3); t = 0.89 second (4); t = 0.92 second (5); t = 0.94 second (6), after the start of the initial opening phase of the first chewing cycle). The mandibular and maxillary molars have been outlined in red and blue, respectively, for ease of distinction.

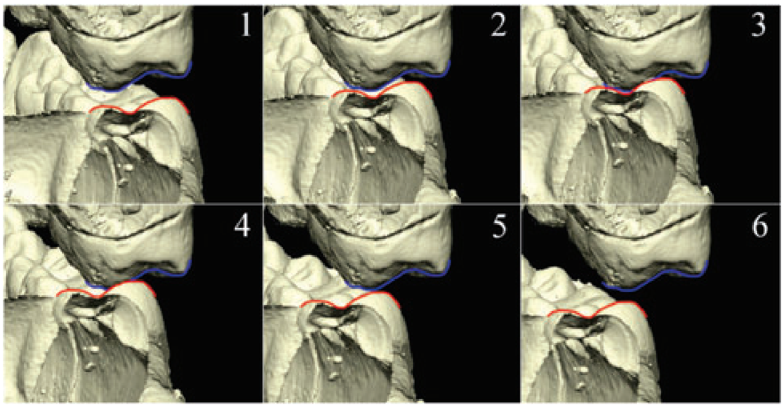

Table 1 Mean distances and the standard deviation between the measured locations of the outermost markers on the mandibular motion-tracking appliance and on the head during chewing elastic and plastic model foods (mm)

Distances between the most distant markers on	Elastic food product (E)		Plastic food product (P)	
	Mean	SD	Mean	SD
Mandibular appliance	66.63	0.069	66.64	0.065
Head	143.52	0.23	143.44	0.23

cycle. The subject, however, did not report any discomfort as a result of the appliance's thickness or acrylic resin component. Nevertheless, future studies using this method should consider the use of a cast metal frame to reduce the thickness of the lingual portion of the appliance, while retaining the necessary rigidity for the clasping system.

The accuracy of the marker recordings with motion-capture systems can be influenced by several factors. These include systematic instrumentation error, random instrumentation error, or errors in placing markers at locations where soft tissue deformations play a significant role. Systematic instrumentation errors associated with the measuring system have been reduced or quantified by calibration and static tests, respectively. Random instrumentation errors typically refer to the automatic digitization process of the captured images or shape distortions resulting from velocity effects or partially covered markers. The upper head markers were placed at locations with minimal skin movement. The custom-made appliance allowed the perioral markers to be rigidly fixed to the mandibular teeth and to the mandible. Furthermore, particular care was taken in the design stage of the mandibular appliance to minimize interference and contact with the lips. Hence, the following error analysis focuses on quantifying the spatial resolution of the system setup and the instrumentation error.

The intermarker distances provide several insights into the quality of the recorded data. The distances between the markers on the brace were rigidly fixed and were assumed to be constant. Deviations from a constant value offered an indication of the instrumentation error. The same applied to the head markers. In contrast to the markers on the appliance, however, the head markers were not rigidly fixed with respect to the skull and, hence, soft-tissue-induced displacements (skin and muscle movement) were expected to be greater than for the markers on the appliance. Therefore, the standard deviation of intermarker distances of the head markers served as a quality measure of the marker placement; the smaller the standard deviation of the intermarker distances, the less the influence of the soft tissue on the marker positions and the more accurate the description of the head movements. (Note that in the ideal case of no noise or measurement errors, all distances would be equal and the calculations of the rigid body movements would have an exact solution.) The mean distances (in mm) between the two outermost markers and their standard deviations for elastic and plastic food samples are listed in Table 1. These standard deviation values for the mandibular appliance are in agreement with those reported for a similar optical system (an Optotrak motion-capture system).[40]

The higher standard deviation values reported in Table 1 for the two most distant head markers versus the two most distant mandibular appliance markers (0.069 and 0.065 for the mandibular markers vs. 0.23 for the head markers) were small enough that errors induced by skin movement were thought not to have a significant influence for the calculation of the rigid body motions. An additional and implied assumption for rigid body motions requires that the object in motion, in this case the mandible, can be considered to be rigid. The mandible, consisting of cancellous and cortical bone, deforms under the influence of (muscle) forces. The muscle forces, however, deform the mandible only by small amounts,[41-43] and hence the authors' assumption of treating the mandible as a rigid object was justified.

Besides measurement errors of the recording device, the combined model of 3D chewing trajectories and subject-specific models of the teeth relied on the ability to occlude the geometrical representations of the maxillary and mandibular teeth and to link them to the initial recording position within the virtual model. After reconstructing the pins, it was noted that the distance between the tips of the left and right pins differed between the mandibular and maxillary reconstructed model by 0.18 mm (47.73 mm vs. 47.55 mm). This deformation of the pins could be due to the clipping of the pins, handling of the casts, or the reconstruction and segmentation algorithm applied to the sets of images obtained from the μ-CT; however, the measured difference was considered to be minimal for this application.

In general, the use of the appliance did offer some advantages over the articulograph. First, articulographs recording with six DOF are not as widely applicable and accessible as optoelectronic motion-capture systems. Most importantly, the required receiver coils, which are glued onto the teeth, have a tendency to be cut during the masticatory sequence and could have resulted in losing data. One of the disadvantages of the new technique is that individually tailored appliances are required for each subject.

Clinical implications

The methodology presented within this article provides a significant advancement in analyzing mandibular movement with several instant applications in the fields of dentistry, behavioral sciences, the food-processing industry, and biomechanics. In dentistry, for example, this methodology could aid in investigating the effects of fixed and removable partial dentures on occlusion and, also, differing jaw shapes on chewing behavior. Further, it may be used as a diagnostic tool for abnormal chewing behavior or as a teaching tool, that is, characterization of normal and/or abnormal chewing. In the field of behavioral sciences and in the food-processing industry, there is currently much interest in modeling the human masticatory system in order to get a better understanding of the effects of changing food properties on mastication and digestion and the impact of aging on mastication and food choice. In the field of biomechanics, the visualization tool and the chewing trajectories can be used as kinematic input to computer simulations analyzing their influence on the human masticatory process in three dimensions.[44,45] In prosthetic dentistry, this methodology can by used by dental CAD software developers to build a database of average chewing trajectories and produce a dynamic virtual articulation that may enable the removal of eccentric premature occlusal contacts before milling restorations. All such studies should benefit from the greater detail provided by the combination of accurately capturing 3D movements of the teeth.

Conclusion

This report presented a methodology in which mandibular movements were measured during mastication, and the kinematic input for a 3D computer model was calculated to form virtual dynamic articulation suitable for dental CAD/CAM software. The method may also be applied to analyze mandibular movement and mastication within the fields of dentistry, behavioral sciences, and biomechanics and the food-processing industry.

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