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Short communication

Kinematic study of the mandible using an electromagnetic tracking device and custom dental appliance: Introducing a new technique ☆

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Abstract

The purpose of this study is to introduce a new technique for recording the kinematics of the temporomandibular joint and incisors, using an electromagnetic tracking device and custom dental appliance. Five normal subjects took part in this kinematic study (4 females, 1 male, mean age of 34.8 years). Subjects' mandibular motion during maximal opening tasks were recorded on two different days and linear distance (LD) (i.e., the LD between the start and end position) and curvilinear path (CP) (i.e., the curvilinear distance along the curve between the start and end position) were calculated for the lower incisor landmark and both condyles in the sagittal plane (in mm). In the present study, the range of incisal movements (LD: 34.9 to 54.3 mm, CP: 36.5 to 60.3 mm) and that of condylar movements (LD: 7.5 to 25.3 mm, CP: 10.6 to 27.6 mm) in the sagittal plane during opening are in the normal range compared to the previous literature. The ability of subjects to reproduce the same motion between the two sessions was also calculated. Differences due to trial sessions and different repetitions within a session were negligible, indicating that the method can be used to assess changes between testing conditions in healthy subjects, and patients pre- and post-operatively.

Keywords: Kinematics; Temporomandibular joint; Method

1. Introduction

Temporomandibular joint (TMJ) function has been traditionally assessed by border movements of the mandibular incisors. As the mandibular condyles and incisors are part of one rigid bony system, they move together and it has often been assumed that measurement of incisor movement provides accurate information about condylar movement. However, in many reports, no correlations were found between the incisors and condyles during movement (Buschang et al., 2001; Larheim et al., 1985; Lewis et al., 2001; Szentpetery, 1993; Travers et al., 2000).

There has been an evolution in the development of devices and methods used to record the motion of the mandible (Buschang et al., 2001). Initial efforts used clutches that attached to the teeth and recorded motion in two-dimensional (2D) (Gibbs et al., 1971). Later, methods utilized cinematography which required digitization of film; generally only measured data in 2D; and visualization of the structures was limited by the skin and lips (Ahlgren, 1966, 1967). Videofluoroscopy (Cleall, 1965; Hamlet et al., 1997) allowed greater visualization of the bony structures, but this method exposes patients to ionizing radiation. Optoelectric methods using light-emitting diodes (LED) bonded to the lower anterior teeth have been widely used for recording jaw motion, and were originally introduced by Karlsson, (1977) and Jemt et al., (1979). Registration error in a static state for this method was reported to be

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0.14 mm ± 0.01 mm, and under dynamic conditions, the system had a mean error of 0.27 mm ± 0.04 mm (Jemt and Karlsson, 1982). Correlations between first and second registrations on the same individuals were reported as varying between 0.8 and 0.9 (Karlsson and Carlsson, 1990). However, because only one LED was attached to the lower incisors, only 3D data on the tracking of this one point (i.e. lower incisors) was obtained, with no data reported on the overall 3D motion of the mandible. Buschang et al., (2001) used an optoelectric method with a clutch supporting four LEDs that was bonded with Fuji LC ® to the lower incisors. They were able to obtain 3D data of mandibular motion, however, the mean difference between repeat measurements on the same individuals was as high as 29% of the mean value for one of the types of movements measured. Additionally, the error of the system was not reported.

Magnetic tracking methods which can track the position of a single magnet have been used, but the accuracy of this system has not been reported (Nakamura et al., 1988; Yamada et al., 1996). Our laboratory has developed a new technique for recording the kinematics of the TMJ and incisors, using an electromagnetic tracking device (3Space Fastrak, Polhemus, Inc.), laptop-based data collection software (The MotionMonitor, Innovative Sports Training, Inc), and custom dental appliances. Previously, the electromagnetic tracking device was calibrated (Zhao et al., 2005) to determine the accuracy of digitizing static points in 3D space. The system was able to discern distances between known positions to an accuracy of 0.32 ± 0.60 mm.

The purpose of this study is to introduce this new technique, assess the error in the recording and analyzing equipment, and comment on the ability of human subjects to replicate maximal mandibular opening tasks between two data collection sessions.

2. Materials and methods

2.1. Subjects

Five healthy individuals (4 female, 1 male, mean age of 34.8 years) participated in the study. All subjects had complete dentitions except third molars (i.e., wisdom teeth) and normal occlusion without obvious abnormalities such as a crossbite. They had no signs or symptoms of a craniomandibular disorder or major dental treatment within the last 3 years (orthodontics, orthognathic surgery, or extensive restorative therapy). The aim and protocol of this study was explained to all participants prior to the start of recording. All subjects provided written informed consent to participate. This study was approved by the authors' Institutional Review Board.

2.2. Data collection

Impressions were taken of the subjects' upper and lower anterior teeth. Custom made plastic dental appliances to fit onto the upper and lower anterior teeth were made with plastic orthodontic brackets (TP Orthodontics, LaPorte, IN) and cold curing acrylic resin. The appliances were bonded to the pre-selected anterior teeth with Fuji Ortho LC ® (GC America Inc., Alsip, IL) according to the manufacturer's instructions, and care was taken to place the appliances so they did not interfere with occlusion or function in any way (Fig. 1).

The participant was then seated in a comfortable upright position in a wood chair with the Frankfort horizontal plane (line which connects the suborbitale with tragus of ear) approximately parallel to the floor. An electromagnetic tracking device (3Space Fastrak System, Polhemus, Colchester, VT) (static accuracy of 0.8 mm RMS for translation, 0.15° RMS for orientation) and accompanying software (The MotionMonitor, Innovative Sports Training, Inc., Chicago, IL) were used to record the 3D kinematics of the mandible relative to the temporal bone. This was achieved by attaching one electromagnetic sensor to the upper and one to the lower plastic brackets. The magnetic source was placed posterior to the patient's shoulder just inferior to the height of the sensors using a Plexiglas mounting bracket. A custom, calibrated Plexiglas digitizing probe was used to locate anatomical points for defining the anatomical coordinate systems and for defining landmarks of interest.

The mandible and temporal bone coordinate systems (origin on the upper central incisor) were constructed prior to data collection with the subject in the molar bite position (Fig. 2). The Z-axis direction was defined as the vector defined by the right and left mesiobuccal cusps of the lower 1st molars (point 1 to 2). The X-axis direction was defined as the perpendicular to the plane defined by

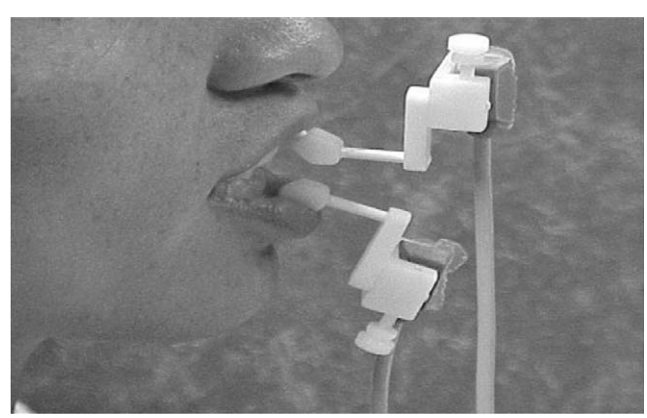

Fig. 1. Custom dental appliances and plastic brackets with electromagnetic sensors attached.

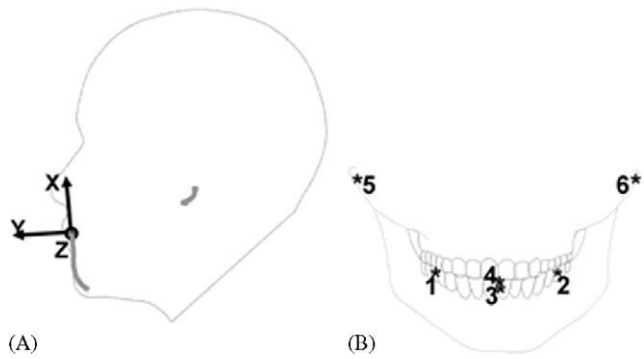

Fig. 2. (A) Coordinate system and trajectories (in gray) of condylar and incisor motion in the sagittal plane from a representative subject. (B) Digitized anatomical landmarks used for defining anatomical coordinate systems. *Z*-axis direction corresponds to the vector defined by the right and left mesio-buccal cusps of the lower 1st molars (point 1 to 2). *X*-axis direction is defined as the perpendicular to the plane defined by points 1,2 and 3 (the mid-superior edge of the lower central incisors). The *Y*-axis is defined as the cross-product of the *Z* and *X* vectors. The origin of the coordinate system is located at point 4 (the mid-inferior edge of the upper central incisors). Four anatomical landmarks were used to monitor condylar and incisor motion, the mid-superior edge of the lower central incisors (point 3), the mid-inferior edge of the upper central incisors (point 4) and the lateral pole of the right and left TMJ condyles (points 5 and 6).

points 1,2 and 3 (the mid-superior edge of the lower central incisors). The *Y*-axis was defined as the cross-product of the *Z* and *X* vectors. The origin of the coordinate system was located at point 4 (the mid-inferior edge of the upper central incisors). In addition, four anatomical landmarks, the mid-superior edge of the lower central incisors, the mid-inferior edge of the upper central incisors and the lateral pole of the right and left TMJ condyles were digitized to be tracked in 3D space (Fig. 2). The positions of the anatomical condylar points were determined by palpating the deepest point of condylar fossa curvature during opening and closing movements of the mouth and digitizing reference points 5 mm inferior from the palpated points. It is not critical to obtain an accurate and reproducible location for the condyles since all points in the general vicinity of the condyles would move in a similar magnitude and direction.

Six repetitions of maximal opening–closing movements were performed at a rhythm of approximately 0.5 Hz (i.e. a full opening–closing cycle every 2 s). The subjects were instructed to perform each movement maximally, symmetrically and as smoothly as possible. Each movement started and ended in the maximum intercuspal position (i.e., the bite position). Before each recording, the participants were given the opportunity to practice the required task. Position and rotation of the mandible were obtained dynamically in the anatomical coordinate system during opening–closing movements.

After jaw motion was recorded, the plastic devices were removed with an orthodontic de-bonding instrument. Any residual adhesive on the teeth was removed with hand or rotary instrumentation. After at least 2 months had passed, the five subjects were retested to determine the source of the variation between the first and second recordings.

2.3. Data analysis

Three repetitions with the greatest motion of the lower central incisor were selected from each subject's data for analysis.

The opening portions of the movements only were selected from the time series data for the three repetitions. The linear distance (LD) (i.e., the LD between the start and end position) and curvilinear path (CP) (i.e., the curvilinear distance along the curve between the start and end position) were calculated for the lower incisor landmark and both condyles in the sagittal (*X*–*Y*) plane (in mm). The total deviation of the lower incisor (i.e., distance from greatest left deviation to greatest right deviation) was calculated in the frontal (*X*–*Z*) plane (in mm).

The data analysis consisted of fitting a three-factor analysis of variance (ANOVA) model, with subject, trial session (2 levels) and repetition (3 levels) handled as three random effects. The restricted maximum-likelihood method (REML) was used to estimate the variance components for each of the main factors along with the two-way interactions using the SAS procedure PROC VARCOMP (SAS Institute, Cary, NC).

3. Results

The results of the mandibular incisor movements during the opening movements for the five subjects, averaged both across the three repetitions within a trial session and across all subjects, separately for the two trials, are shown in Table 1. In the sagittal plane, the average length of the LD was 41.0 mm (range from 34.9 to 49.8 mm) in the original test trials and 43.9 mm (range from 35.4 to 54.3 mm) in the retest trials. The average length of the CP was 43.4 mm (range from 37.4 to 51.5 mm) and 46.6 mm (range from 36.5 to 60.3 mm) in the original test and retest trials, respectively. Fig. 3 depicts the original and retest incisal LD for all five subjects.

The results of the condylar movements during the opening movements in the sagittal plane, averaged both across the three repetitions within a trial session and across all subjects, separately for the two trial sessions are shown in Table 2. The mean right condyle LD was 16.1 mm (range from 11.4 to 25.3 mm) in the original trial session and 13.3 mm (range from 7.5 to 21.2 mm) in the retest trial sessions. The mean left condyle LD was 15.4 mm (range from 10.2 to 20.0 mm) in the original

Table 1
Original (*O*) and retest (*R*) results for the incisor LD and CP during opening movements for five normal subjects (mean, mm)

Subject	Incisor (sagittal plane)				Incisor (frontal plane)	
	LD		CP		Deviation	
	O	*R*	*O*	*R*	*O*	*R*
1	36.6	38.7	39.6	40.4	1.5	1.7
2	49.8	45.1	51.5	47.4	0.6	1.3
3	48.1	54.3	51.2	60.3	3.7	1.3
4	35.8	45.9	37.4	48.2	0.7	0.8
5	34.9	35.4	37.4	36.5	1.2	1.9
Mean (SD)	41.0 (7.3)	43.9 (7.3)	43.4 (7.3)	46.6 (9.1)	1.5 (1.3)	1.4 (0.4)

LD: linear distance; CP: curvilinear path; *O*: original; *R*: retest; SD: standard deviation.

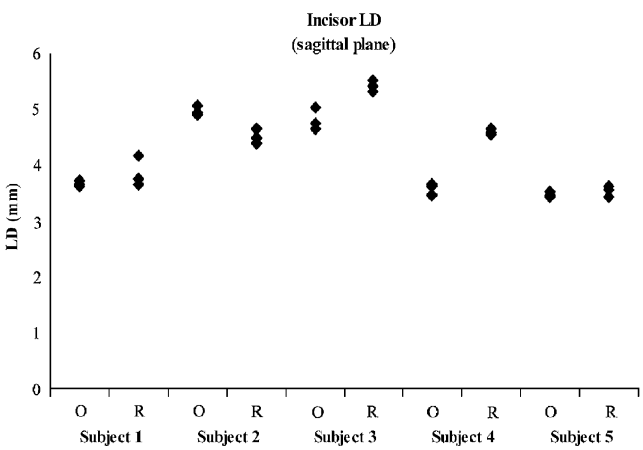

Fig. 3. Incisor sagittal plane linear distance (LD) for the three repetitions in the original (*O*) and retest (*R*) data collection for the five subjects.

trial session and 12.7 mm (range, 8.3 to 18.2 mm) in the retest trial session.

Estimates of the variance components are summarized in Table 3. For all measures, most of the variation could be attributed to between subject variation and the subject *x* trial session interaction. However, the amount of variation attributed to the two sources differed across measures. Subject *x* trial session interaction is most likely due to the fact that some subjects had greater measures in their original session, whereas others had greater measures in their retest session. Differences due to trial sessions and likewise different repetitions within a session were negligible.

4. Discussion

The authors of the present study were concerned with minimizing the equipment attached to the subject to allow free movement of the head so as to not influence the natural pattern of mandibular movements. In the present study, the authors studied the kinematics of TMJ function in healthy individuals using an electromagnetic tracking device and custom dental appliance. This system may be less cumbersome than other methods which utilize an eyeglass frame with head strap for recording the kinematics, and attachment of the appliance not only to the teeth but also intraoral soft tissues (gingival and vestibular areas) (Donzelli et al., 2004; Naeije, 2002; Youssef et al., 1997).

The acrylic appliance made by the authors was attached onto only three anterior teeth in the upper and lower jaw, respectively, without interfering with occlusion and function because its size was small. Moreover, the plastic appliance allowed the plastic brackets and sensors to be rigidly fixed to the teeth. This created a situation where the mandible and associated teeth, dental appliance, and sensor could be considered as a single rigid body (Panjabi, 1979). The techniques to attach and remove the custom dental appliances all followed the manufacturers' instructions. The method used can be routinely performed by dentists with expertise in orthodontic bonding techniques.

In the present study, the range of incisal movements in the sagittal and frontal plane and that of condylar movements in the sagittal plane during opening are in the normal range compared to the previous literature (Fukui et al., 2002; Travers et al., 2000; Youssef et al., 1997). In addition, the source of variation for the incisal and condylar measures were quantified. It was determined that the majority of the variance could be attributed to the inter subject differences and the subject *x* trial session interaction. Differences due to trial sessions and different repetitions within a session were negligible, indicating that the method can comfortably used to assess changes between testing conditions in healthy subjects, and patients pre- and post-operatively.

Table 2
Original (*O*) and retest (*R*) results for the condylar LD and CP during opening movements for five normal subjects (mean, mm)

Subject	Right condyle (sagittal plane)				Left condyle (sagittal plane)			
	LD		CP		LD		CP	
	O	*R*	*O*	*R*	*O*	*R*	*O*	*R*
1	11.4	15.3	17.0	18.9	14.4	18.2	17.7	19.7
2	19.7	11.8	23.6	16.1	19.1	8.3	23.9	11.9
3	25.3	21.2	27.6	27.3	20.0	15.2	23.7	21.9
4	12.3	10.5	14.3	14.2	10.2	12.2	11.6	14.0
5	12.0	7.5	16.0	10.6	13.5	9.7	15.9	12.1
Mean (SD)	16.1 (6.1)	13.3 (5.2)	19.7 (5.7)	17.4 (6.3)	15.4 (4.1)	12.7 (4.0)	18.6 (5.3)	15.9 (4.6)

LD: linear distance; CP: curvilinear path; *O*: original; *R*: retest; SD: standard deviation.

Table 3
Variance components for the incisal and condylar measurements

Source of variation	Incisor (sagittal plane)		Incisor (frontal plane)	Right condyle (sagittal plane)		Left condyle (sagittal plane)	
	LD	CP	Deviation	LD	CP	LD	CP
Subjects (*S*)	37.21	46.92	0.16	23.09	27.57	0	7.27
Trial session (*T*)	0.91	0.81	0	2.20	1.01	0.37	0.04
Repetitions (*R*)	0.45	1.77	0.01	0	0.32	0	0.16
$S \times T$	15.34	20.21	0.62	9.56	7.68	16.39	16.88
$S \times R$	0	0	0	0.01	0.65	0	0.16
$T \times R$	0	0	0	0	0.05	0	0
Error	1.25	2.09	0.13	0.13	0.88	0.06	0.48

LD: linear distance; CP: curvilinear path.

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