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Relevance of mandibular helical axis analysis in functional and dysfunctional TMJs

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Abstract

The helical axis (HA), or motion screw, yields a comprehensive description of joint motion. The perspective representation of this axis clearly visualizes the regularity of mandibular functional movements (Yatabe et al. 1997. Journal of Dentist Research 76, 714–719 and Gallo et al. 2000. Journal of Dental Research 79, 1566–1572). In this study, the sensitivity of the HA representation was investigated relative to (a) irregularities in pathologic motion of clicking temporomandibular joints (TMJs) for jaw opening/closing and (b) differences in food bolus size and consistency for unilateral mastication in subjects with normal TMJs. Mandibular motion relative to the head was acquired using a jaw tracker with six degrees-of-freedom with a sampling frequency of 70 Hz. The HA was calculated according to an eigenvalue method (Spoor and Veldpaus 1980. Journal of Biomechanics 13, 391–393) and parameters were defined describing its position and orientation relative to the anatomy. We analyzed 39 subjects with unilateral or bilateral reciprocal TMJ clicking during jaw opening/closing and seven asymptomatic subjects during unilateral mastication of five different types of soft and hard food in two different bolus sizes. The results showed a greater variability of the HA parameters in the group of clicking joints than in the asymptomatic group: in particular, the area in which the HA moved was wider in clicking joints than in normal ones and the HA in clicking TMJs had a much greater fluctuation than in normal ones. During unilateral mastication, for more consistent food or a bigger bolus the HA showed a significantly greater excursion of the orientation parameters. Furthermore a significantly greater excursion of the dorsoventral and of the craniocaudal component of the distance vector from the HA to the condyle were found. The helical axis analysis of mandibular movements was sensitive to kinematic irregularities of the mandible due to an internal joint derangement as well as to differences in food bolus size and consistency.

Keywords: Jaw kinematics; Helical axis; Temporomandibular joint; Chewing; Clicking joints

1. Introduction

Although muscles produce linear forces only, joint motions in the human body have a strong rotary component in almost all instances. Joints with high congruency of the articulating surfaces and surrounding tissue constraints—such as the ulnohumeral joint—can be considered as hinge joints. However, at least theoretically, any joint rotates around an instantaneous axis. This instantaneous axis of rotation mostly changes its spatial position and orientation during joint movements and is best described by the helical axis (HA), also called screw axis or motion screw (Phillips, 1984). In this representation, the infinitesimal spatial motion of a joint segment is expressed as the combination of a translation along this axis and a rotation around it (Spoor and Veldpaus, 1980; Woltring et al., 1985).

The use of the HA yields a comprehensive description of the joint kinematics and its perspective representation clearly visualizes the movement progression (Fioretti et al., 1990; Woltring et al., 1994). The assessment of HA parameters has proven effective in the description and differentiation of functional and dysfunctional joint

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movements (Ramakrishnan and Kadaba, 1991; Jonsson and Karrholm, 1994; Feipel and Rooze, 1999; Baeyens et al., 2001). Furthermore, the calculation of moment arms of the muscles involved in the motion relative to the HA gives an insight into the activation patterns of these muscles and their relative contribution to a specific action (Boyd and Ronsky, 1998; Wilson et al., 1999; Gal et al., 2004).

The HA has been used to study in vivo the kinematics of various human joints, such as for instance the elbow (Stokdijk et al., 1999), the neck (Woltring et al., 1994), the spine (Dimnet and Guinguand, 1984), the shoulder (Stokdijk et al., 2000), the knee (Hart et al., 1991; Weidenhielm et al., 1993; Jonsson and Karrholm, 1994) the wrist (Zdravkovic et al., 1994; Feipel and Rooze, 1999; Salvia et al., 2000) and the temporomandibular joint (TMJ) (Gallo et al., 1997; Gallo et al., 2000; Gal et al., 2004). Only few studies though implemented an approximation of the instantaneous HA, generally obtained by means of tracking systems with at least six degrees-of-freedom based on external optical markers (Fioretti et al., 1990; Hart et al., 1991; Woltring et al., 1994; Gallo et al., 1997; Salvia et al., 2000).

The HA model is useful for a comprehensive kinematic description also of mandibular motion, especially as the traces of single mandibular points—extensively used in the past to study mandibular movements (Merlini and Palla, 1988; Rohrer et al., 1991; Salaorni and Palla, 1994; Yatabe et al., 1997; Huddleston Slater et al., 1999; Slater et al., 2002)—do not reveal the true nature of the movement as a whole (Morneburg and Proschel, 1998; Travers et al., 2000; Lewis et al., 2001) or reflect only particular types of movement (Peck et al., 1999). Studies on subjects with a normal masticatory system showed that during jaw opening/closing the total rotation around the HA was $24.3^\circ \pm 4.2^\circ$, the translation along it 0.9 ± 0.7 mm and its distance from the condyle 48.9 ± 9.9 mm (Gallo et al., 1997).This indicated a negligible mediolateral deflection of the mandible and that the HA was never localized within the condyle but often even outside the mandible. Furthermore, the pathways fluctuated only slightly, they were smooth and varied interindividually.

TMJ clicking is a most common symptom of craniomandibular disorders and is probably connected to a sudden, relative translatory movement of the disc in relation to the condyle which causes a sudden mandibular acceleration (Helkimo, 1974; Hansson and Nilner, 1975; Helkimo, 1979; Klett, 1982; Wanman and Agerberg, 1986; Agerberg and Inkapool, 1990; Kononen and Nystrom, 1993). Few researchers studied mandibular movements three-dimensionally in patients with clicking TMJs (Klett, 1982; Ernst, 1988; Rohrer et al., 1991; Slater et al., 2002). Velocity profiles of intracondylar points were evaluated and a high intraindividual variability of condylar velocity at clicking as well as a great variability of the condylar paths were found (Isberg-Holm and Westesson, 1982), some of the paths being however very similar to those of asymptomatic subjects (Ernst, 1988). Since the HA model appears to be highly sensitive to motion irregularities, one can postulate that it could better be suited to characterize abnormal movements.

Also for mastication the HA model provides a compact representation of mandibular kinematics (Gallo et al., 2000). During unilateral mastication of bread cubes with 2-cm side the HA changes orientation and position more during the closing than during the opening phases. Also, the distance between HA and mandibular condyle varies more significantly on the chewing (working) than on the non-chewing (balancing) side, strongly increasing on the balancing side during closing. This indicates that, during this phase of the chewing cycle, the condyle on the balancing side still translates backward while essentially only rotation occurs around the condyle on the working side (working or chewing side refers to the side where the food is chewed; the balancing or non-working side is the opposite side).

Masticatory movements are influenced by consistency, dimension and texture of the food (Hannam et al., 1977; Gibbs et al., 1981; Thexton, 1992; Howell et al., 1993; Takada et al., 1994; Palla et al., 1997). For instance, tough food is chewed with wider lateral excursions than soft food. The size of the food particles determines the degree of mandibular opening and the interocclusal distance decreases progressively along with food comminution. Therefore, it is expectable to find this variability of the masticatory movements reflected also in differences of the patterns of the HA pathways.

The aims of this study were twofold: first, to determine the helical axis parameters in a group of subjects with TMJ reciprocal clicking and to investigate whether they provide a good discrimination between patients and asymptomatic subjects, and secondly, to analyze the helical axis pathways for mastication of food boluses of different size and consistency.

2. Materials and methods

2.1. Subjects

Potential subjects were interviewed on medical and specific TMJ dysfunction histories, according to the clinic's protocol: pain or sounds in the TMJ, pain or fatigue in the masticatory muscles, impaired jaw mobility, facial pain, headache and toothache [details in previous work (Palla, 1986; Salaorni and Palla, 1994)]. The subjects underwent a clinical examination: measurement of active and passive mandibular mobility; occlusal analysis Angle class, overbite and overjet analysis; palpation and auscultation of the TMJs; palpation of masticatory, neck and shoulder muscles [details in previous work (Gallo et al., 1997)]. An informed verbal consent to participate in the study was obtained from all subjects. The study protocol was approved by the ethical committee of the Center for Dental and Oral Medicine and Maxillofacial Surgery.

The analysis of opening/closing movements was performed on 39 dentate subjects (31 females and 8 males) aged 26–51 years (mean age 26 years) with unilateral or bilateral reciprocal TMJ clicking that disappeared when the subjects opened and closed from a protruded jaw position. This led to the clinical diagnosis of an anterior disc displacement with reduction. The study on mastication was carried out on eleven asymptomatic subjects (7 females and 4 males) aged 25–39 years (mean age 30 years) without a history of signs and symptoms of myoarthropathies of the masticatory system, i.e. of craniomandibular disorders, in particular without any TMJ clicking.

Inclusion criteria for all patients as well as asymptomatic subjects were: maximum opening >40 mm (overbite included), protrusion and laterotrusion >7 mm (Helkimo, 1974), and difference between active and passive maximum opening <2 mm (Palla, 1986).Wear facets were accepted, provided the provocation test was negative (Krogh-Poulsen, 1973). Asymptomatic subjects had mandibular deviation and/or deflection <2 mm. At the time of recording all patients and asymptomatic subjects were negative at TMJ and muscle palpation, however, some of the patients with TMJ clicking had episodes of jaw locking, or discomfort, which were almost always related to mastication.

2.2. Jaw tracking

Jaw movements were recorded by means of the optoelectronic system Jaws-3D (Mesqui et al., 1985; Airoldi et al., 1994), based on the assumption of the mandible as a rigid body. Two triangular target frames, carrying three light-emitting diodes each, defined a head-related *XYZ* coordinate system (Fig. 1a) and a mandible-related *UVW* coordinate system (Fig. 1b). The target frames were mounted on two metal splints, coplanarly in maximum intercuspation, close to the TMJ and perpendicular to the Camper plane. The splints, non interfering with occlusion, were glued to the maxillary and mandibular dental arches.

Mandibular motion relative to the head was recorded as the time-dependent rotation matrix, $\boldsymbol{R}(t_i)$, and the translation vector, $\boldsymbol{v}(t_i)$, for every time sample (sampling frequency 70 Hz). The position of the condyle relative to the mandibular target frame was determined by palpating the lateral condylar pole, marking a point on the skin, determining its *UVW* coordinates with an LED pointer, and displacing the W coordinate medially by 15 mm, thus obtaining a point (CP) located within the condyle (Fig. 1b) (Gallo et al., 1997).

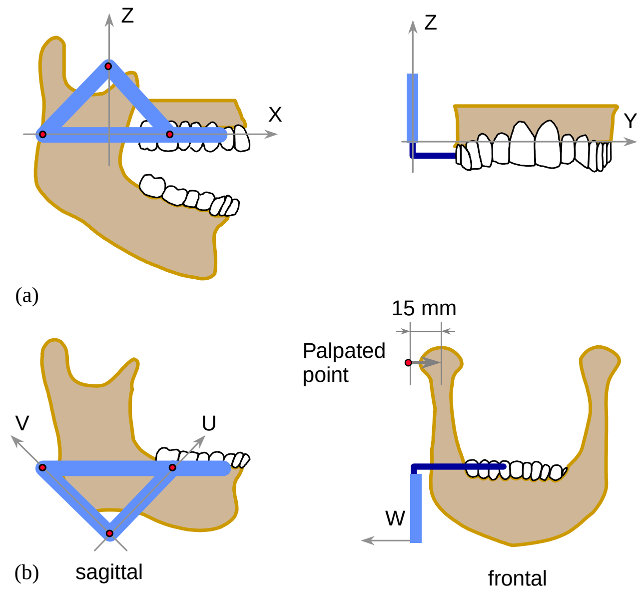


Fig. 1. Jaw tracking system. Target frames and maxillary (*XYZ*) and mandibular (*UVW*) coordinate systems.

2.3. Experimental procedure

The subjects sat comfortably upright on a conventional dental chair with unsupported head and the feet resting on the floor. For the study on jaw opening/closing, each subject performed four consecutive cycles at deliberate rate. The opening/closing cycles had to start and end in maximum intercuspation and to reach maximum opening. For the analysis of masticatory movements, the subjects were presented four different types of food of different hardness (dried beef, bread with crust, cheese, apple). These were cut in cubes with 1.0 cm side, except for bread and apple, also prepared in 2.0 cm side cubes. In addition, the subject had to chew one piece and two pieces of chewing-gum, respectively. The different foods were always chewed in the same order and always on the side of the target frames in two sets of recordings on both sides.

2.4. Data analysis

Prior to data analysis, the trajectories of the target-frame LEDs were low-pass-filtered for noise reduction by means of a nine-coefficient FIR filter, dimensioned according to the Parks-McClellan method (McClellan et al., 1973; Leistner and McClellan, 1975) (pass band between 0 and 5 Hz and suppression band between 20 and 35 Hz).

The HA was calculated by means of an eigenvalues method (Spoor and Veldpaus, 1980). The rotation $\Delta\phi(t_i)$ around the HA and the translation $\Delta T(t_i)$ along it were calculated for each sample time except when very small rotation angles occurred between consecutive motion steps. Indeed, a threshold rotation value was set empirically, below which the HA was not defined. For these motion steps, the movement was considered to consist only of translation.

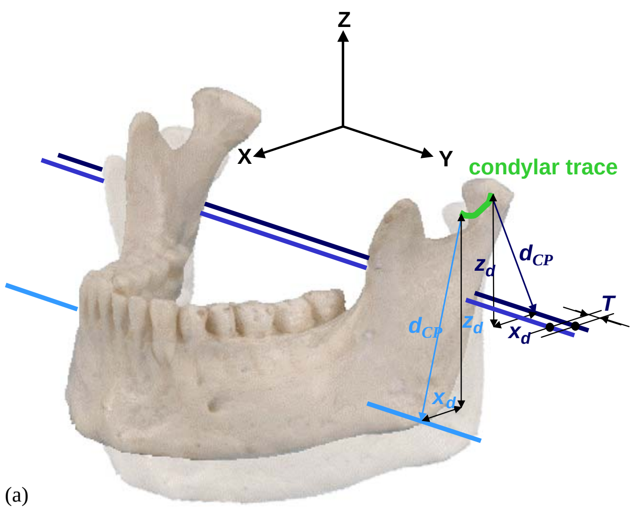
For the sample times in which the HA was defined, the vector $\boldsymbol{d}_{\mathrm{CP}}(t_i)$ (components $x_d(t_i)$, $y_d(t_i)$ and $z_d(t_i)$) was determined, pointing from the condylar point CP perpendicularly to the HA (Fig. 2a), and the angles $\theta_x(t_i)$, $\theta_y(t_i)$ and $\theta_z(t_i)$ between the HA orientation and the reference axes XYZ (Fig. 2b). From these quantities following parameters were calculated: the total rotation around the HA ($\phi_{\max}$), the maximum translation along it ($T_{\max}$), the maximum length of $\boldsymbol{d}_{\mathrm{CP}}(t_i)\,(d_{\mathrm{CPmax}})$, the maxima and minima of $x_d(t_i)$ and $z_d(t_i)\,(x_{\mathrm{dmax}}, x_{\mathrm{dmin}}, z_{\mathrm{dmax}}$ and $z_{\mathrm{dmin}})$, the mean angles $\overline{\theta}_x$, $\overline{\theta}_y$ and $\overline{\theta}_z$ and the mean global fluctuation of the HA spatial orientation ($\overline{\theta}_e$). The latter was calculated by averaging

$$\theta_e(t_i) = \sqrt{[\theta_x(t_i) - \overline{\theta_x}]^2 + [\theta_y(t_i) - \overline{\theta_y}]^2 + [\theta_z(t_i) - \overline{\theta_z}]^2}$$

over all sample times t_i in which the HA was defined. Data collected from both sides were averaged since they had no statistically significant differences [details in previous work (Gallo et al., 1997)].

Opening/closing. The HA was calculated at 14 ms intervals, except when rotation angles below a threshold value of 0.25° occurred between consecutive motion steps. For these time samples the movement was considered as merely translatory. The rotation threshold value was set lower than in asymptomatic subjects (1.0°), due to the generally lower opening/closing frequency. Statistical differences between the HA parameters $\phi_{\max}, T_{\max}, d_{\mathrm{CPmax}}, x_{\mathrm{dmax}}, x_{\mathrm{dmin}}, z_{\mathrm{dmax}}, z_{\mathrm{dmin}}, \overline{\theta}_x, \overline{\theta}_y, \overline{\theta}_z$ and $\overline{\theta}_e$ calculated from the normative group (Gallo et al., 1997), and the joint clicking group were analyzed by means of t-tests with a level of significance of $p<0.05$.

Mastication. The differences between the maxima and minima of the orientation parameters $\theta_x(t_i)$, and $\theta_z(t_i)$ and of the position parameters $d_{\mathrm{CP}}(t_i), x_d(t_i)$ and $z_d(t_i)$ were determined for all closing phases and averaged over the entire chewing sequence for each food type and each subject. These values represented the average excursion of the HA parameter during the closing phase. Differences between the parameters obtained from the left and right-sided chewing were analyzed statistically by means of paired t-tests. ANOVA for repeated measurements was used to analyze the data for differences among different food types and sizes. Differences of statistical significance were based on values of $p<0.05$.



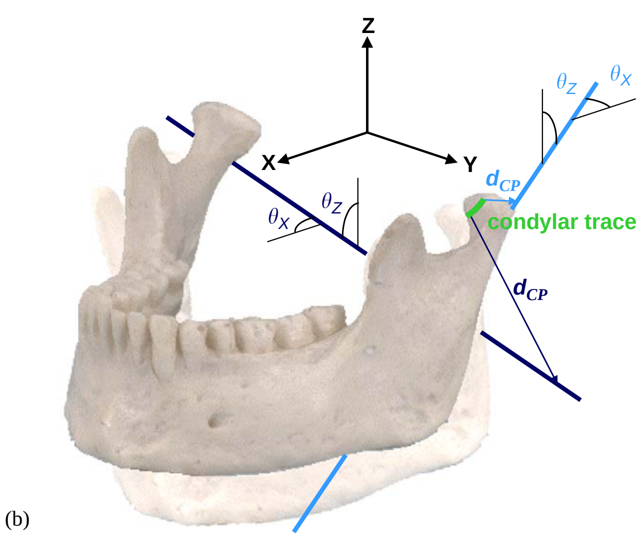


Fig. 2. Definition of mandibular helical axis parameters. The mandible is represented at maximum intercuspation and semitransparent at maximum opening, together with the maxillary coordinate system (XYZ) and condylar traces. (a) Symmetric mandibular movements, such as jaw opening/closing. The vector $\boldsymbol{d}_{\mathrm{CP}}$ points from the condyle perpendicularly to the helical axis ($\boldsymbol{d}_{\mathrm{CP}}$ and its components x_d and z_d are shown for the two extreme mandibular positions). The translation T along the helical axis is shown for two successive mandibular positions. (b) Asymmetric mandibular movements, such as unilateral mastication. The vector $\boldsymbol{d}_{\mathrm{CP}}$ and the angles θ_x and θ_z between the helical axis orientation and the reference axes X and Z of the maxillary coordinate system are shown for the two extreme mandibular positions.

3. Results

3.1. Opening/closing

Fig. 3a shows an example of the mandibular HA pathway of an asymptomatic subject during a jaw opening/closing cycle in a perspective view seen from the subject's frontal left side. The HA during opening (segments in black/blue) and during closing (segments in gray/red) remains almost parallel to itself during the entire movement: this indicates only a small fluctuation. The distance of the HA from the condyle varies. Fig. 3b shows the variation of the HA parameters in the same subject. The small fluctuation of the HA is visible from the parameters $\theta_x(t_i), \theta_y(t_i)$ and $\theta_z(t_i)$ that oscillate within a maximum of about 5°. Also, the negligible

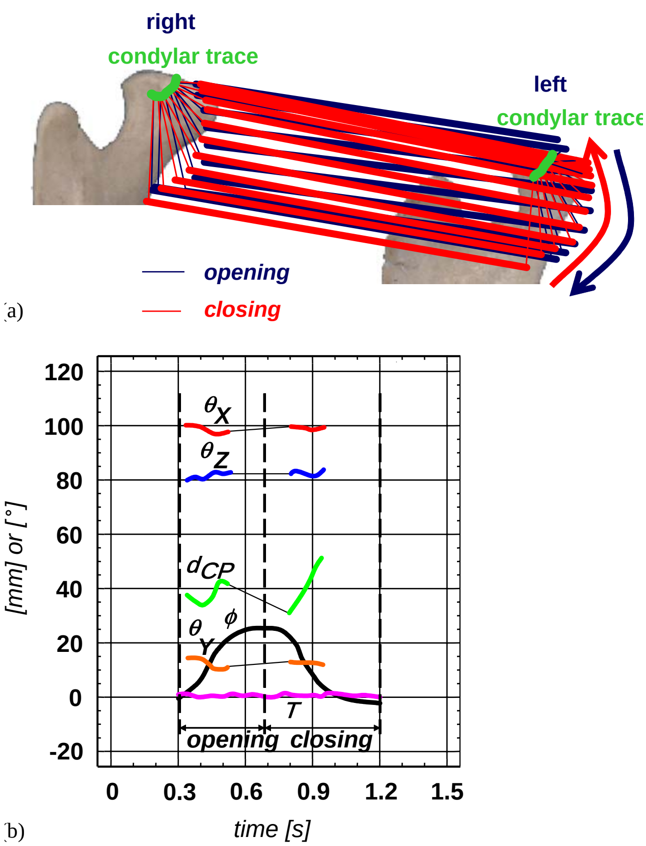


Fig. 3. Helical axis during jaw opening/closing in an asymptomatic subject. (a) The condyles, their traces as well as the distance lines between the condylar traces and the helical axis are represented. The subject looks to the left side of the figure as in Fig. 2. The helical axis at various instants during opening is represented in black/blue and during closing in gray/red. Arrows indicate the displacement of the helical axis along its pathway for opening and for closing. (b) Parameters of the helical axis plotted vs. time. The graph shows the translation T along the axis and the rotation ϕ around it as well as the condyle-axis distance d_{CP} and the angles θ_x, θ_y and θ_z between the helical axis orientation and the axes X, Y and Z of the maxillary coordinate system. Thin lines for $d_{\mathrm{CP}}, \theta_x, \theta_y$ and θ_z indicate that the helical axis is undefined (mandible almost still at maximum opening).

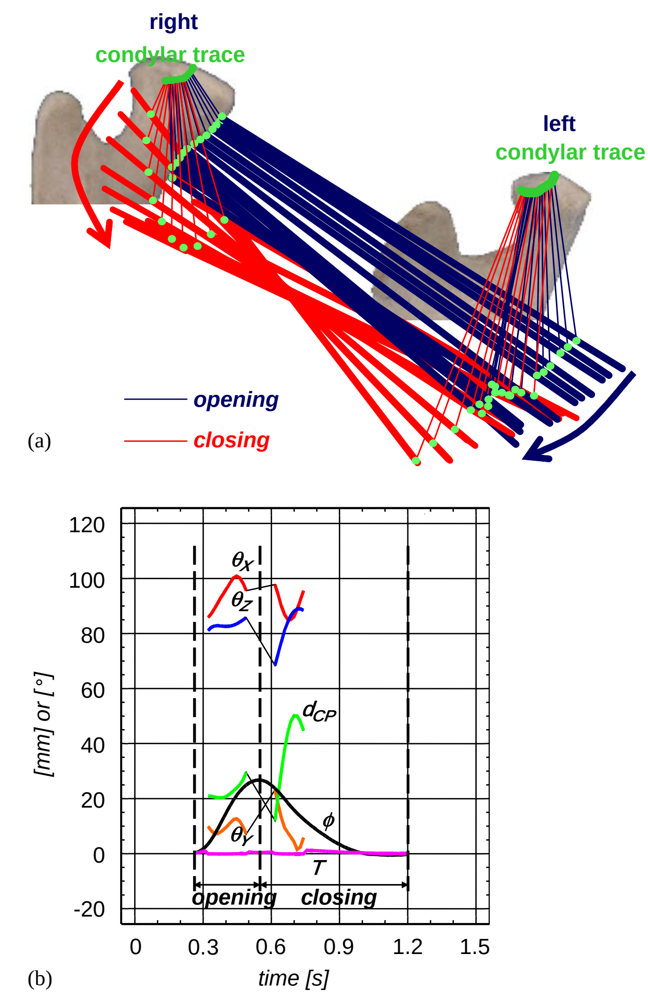


Fig. 4. Helical axis during jaw opening/closing in a patient with TMJ clicking. (a) The condyles, their traces as well as the distance lines between the condylar traces and the helical axis are represented. The subject looks to the left side of the figure as in Fig. 2. The helical axis at various instants during opening is represented in black/blue and during closing in gray/red. Arrows indicate the displacement of the helical axis along its pathway for opening and for closing. The dots at the connection between the helical axis and $\boldsymbol{d}_{\mathrm{CP}}$ (s. Fig. 2) show the irregularity of the movement progression. (b) Parameters of the helical axis plotted vs. time. The graph shows the translation T along the axis and the rotation ϕ around it as well as the condyle-axis distance d_{CP} and the angles θ_x, θ_y and θ_z between the helical axis orientation and the axes X, Y and Z of the maxillary coordinate system. Thin lines for d_{CP}, θ_x, θ_y and θ_z indicate that the helical axis is undefined (mandible almost still at maximum opening).

lateral deflection of the mandible results from the virtually constant values of T. The distance between HA and condyle $d_{\mathrm{CP}}(t_i)$ varies during the whole movement as well as the total rotation ϕ around the HA.

Fig. 4a shows the example of the mandibular HA pathway of a patient with reciprocal clicking, during one opening/closing cycle, in the same perspective view and in the same color coding as in Fig. 3. The HA, at first near the condyle, moves away from it in caudoventral direction, changing progressively its orientation and fluctuating strongly. At the beginning of closing, the HA is located near the condyle. During closing, the HA pathway shows a great fluctuation and a more asymmetric orientation than during opening. In this phase, the distance of the HA from the condyle increases very rapidly. Fig. 4b shows the variation of the HA parameters in the same subject. The fluctuation of the HA at opening is mainly reflected by the change of the parameter $\theta_x(t_i)$ that varies from 85° to 100°. The even stronger fluctuation at closing is described by the combined variation of $\theta_x(t_i)$ and $\theta_z(t_i)$, the latter increasing from 70° to 90°. The pathway at closing is also characterized by a sudden increase of the distance $d_{\mathrm{CP}}(t_i)$ between HA and condyle, that varies from less than 15 mm to over 50 mm.

Table 1 lists the overall means ± SD of the HA parameters of the clicking joints and of a sample of 30 asymptomatic subjects (13 m and 17 f) aged 18–34 years (mean age 26 years) from a former study (Gallo et al., 1997) used as controls. All parameters of clicking joints differed with statistical significance ($p<0.05$) from those of asymptomatic joints, except the mean orientation angles $\overline{\theta}_x$ and $\overline{\theta}_z$. The group of joints with clicking showed a greater variability of their parameters than the asymptomatic group, as visible from the standard deviations. The total rotation ϕ_{max} and the total translation T_{max}, around and along the HA, were on average greater in clicking than in normal joints. The area in which the HA moved was also wider in clicking joints than in normal ones, the means of x_{dmax}, z_{dmax} and d_{CPmax} being greater and those of x_{dmin} and z_{dmin} being smaller in the symptomatic group than in the asymptomatic one. TMJs with clicking had also a much greater mean global fluctuation $\overline{\theta_e}$ than normal TMJs.

3.2. Mastication

As already shown in previous work (Gallo et al., 2000), the HA changed continuously its orientation in space and its distance from the condyle. This occurred far more strongly during the closing phases (Fig. 5b) than during jaw opening (Fig. 5a), but also according to food type and size. Fig. 5c shows an example of the orientation angle θ_x during 20 closing phases of mastication in one subject for bread cubes of 2 cm side. The average excursion of θ_x for this recording was the average difference between the maxima and minima of each segment in the diagram (in this case the average excursion of θ_x was 21°).

Table 2 shows the means ± SD of the excursions of all parameters during the closing phases of unilateral mastication over all subjects for all food types. The excursion of the orientation θ_x of the HA with respect to the dorsoventral direction increased significantly with increasing size of the food bolus as well as from the "bread, apple and cheese" to the "dried meat and chewing-gum" measurements. The same behavior was observed for the excursion of the angle θ_Z between the HA and the craniocaudal direction, which reflected the craniocaudal oscillation of the HA. This means that the HA oscillated more strongly dorsoventrally and craniocaudally when the subjects chewed cubes of food with 2 cm side or two pieces of chewing gum than when they chewed food cut into cubes of 1 cm side or only one piece of gum. Also, the HA oscillated more strongly dorsoventrally and craniocaudally when the subjects

Table 1
Helical axis parameters during jaw opening/closing in asymptomatic and clicking TMJs.

Parameter	Clicking TMJs	Controls	p
ϕ_{max} (°)	28 ± 7	24 ± 4	< 0.05
T_{max} (mm)	2 ± 1	1 ± 1	< 0.05
$d_{Cp\,max}$ (mm)	89 ± 20	49 ± 10	< 0.05
$x_{d\,max}$ (mm)	33 ± 22	5 ± 9	< 0.05
$x_{d\,min}$ (mm)	−58 ± 17	28 ± 5	< 0.05
$z_{d\,max}$ (mm)	12 ± 13	12 ± 7	< 0.05
$z_{d\,min}$ (mm)	−63 ± 17	−44 ± 10	< 0.05
$\overline{\theta}_x$ (°)	91 ± 4	89 ± 4	n.s.
$\overline{\theta}_y$ (°)	16 ± 6	8 ± 3	< 0.05
$\overline{\theta}_z$ (°)	91 ± 4	91 ± 4	n.s.
$\overline{\theta}_e$ (°)	17 ± 8	4 ± 2	< 0.05

Means ± SD.

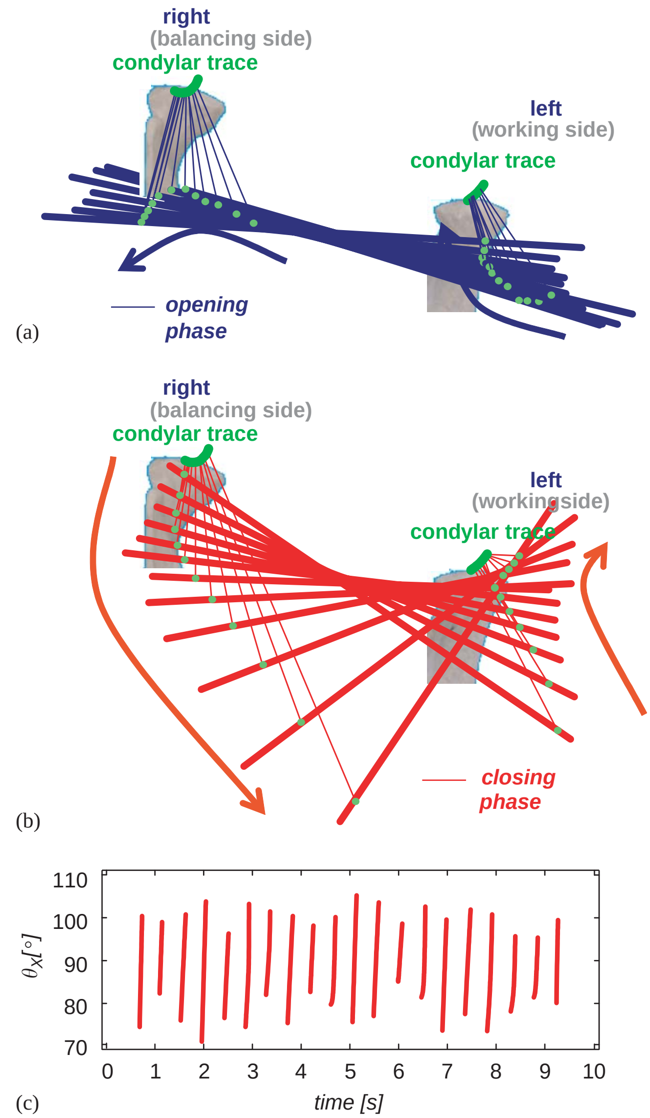


Fig. 5. Helical axis during unilateral mastication in an asymptomatic subject. The subject looks to the left side of the figure as in Fig. 2. Arrows indicate the displacement of the helical axis along its pathway. The dots at the connection between the helical axis and $\boldsymbol{d}_{CP}$ (Fig. 2) show the typical movement patterns. (a) Opening phase. (b) Closing phase. (c) Angle θ_x between the helical axis orientation and the axis X of the maxillary coordinate system plotted vs. time only during the closing phases.

Table 2
Excursions of the helical axis parameters during unilateral mastication: angles Γ_X, Γ_Z (in °) and distances X_{dCP}, Z_{dCP} and d_{CP} (in mm) for food bolus of 1 and 2 cm edge.

Food type	Bread		Apple		Cheese	Dried meat	Gum	
Food size	1 cm	2 cm	1 cm	2 cm	1 cm	1 cm	1 pc	2 pc
θ_x (°)	12±23	18±23	12±14	18±26	13±22	17±39	17±34	21±50
θ_z (°)	21±60	33±93	17±22	28±82	20±59	28±90	31±110	38±165
x_{dCP} (mm)	15±35	20±34	14±32	21±25	16±37	20±45	19±31	20±50
z_{dCP} (mm)	22±65	30±78	18±32	28±70	21±68	28±63	30±78	31±118
d_{CP} (mm)	25±73	33±85	20±51	31±58	25±79	30±76	32±92	33±165

Means±SD.

chewed more resilient food such as dried meat and chewing gum. No statistically significant differences in the oscillation of the HA were found within the subgroups "bread, apple and cheese" and "dried meat and chewing-gum".

The HA did not only change its spatial orientation, but also the excursion of its distance vector d_{CP}, from the condylar point on the working side varied with different size or consistency of the food. For more consistent food or a bigger bolus we found a significantly greater excursion of the dorsoventral component x_{dCP}, of the craniocaudal component z_{dCP} and of the length d_{CP} of d_{CP}. For each parameter, the differences among the data for the five food types in 1 cm side cubes (or the single pieces of chewing-gum) were statistically significant. However, again for each parameter, no statistically significant difference was found within the subgroups "bread, apple and cheese" and "dried meat and chewing gum". The differences among the excursions of x_{dCP}, z_{dCP} as well as d_{CP} depending on food size (1 and 2 cm side cubes as well as 1 or 2 pieces of chewing-gum) were also statistically significant.

4. Discussion

The errors of the method had been assessed statically and dynamically, i.e. performing test movements with the rotation axis stationary as well as moving in space in a previous study (Gallo et al., 1997). Whereas the translation T along the HA had an error of 0.1 mm and the error of the position parameters had a maximum of 1.0 mm for x_d in the sagittal direction, the orientation parameters had a maximum error of 1.9° for θ_x and θ_z and the global fluctuation of the HA 2.6°. These values need to be considered when looking at the quantitative results in Tables 1 and 2 and are negligible if compared to the parameters determined during jaw opening/closing and mastication. This indicates that the recorded variations in the HA pathways recorded during these conditions are really the expression of a biomechanical process.

4.1. Opening/closing

The HA in patients with clicking joints described a less regular path and fluctuated in space far more than in controls. A similar finding has been reported using a slightly different technique, i.e. recording the instantaneous centers of rotation (ICR) (Kordass and Stüttgen, 1997; Sadat-Khonsari et al., 2003). Also these authors reported that the ICR paths of patients with anterior disc displacement with reduction were more irregular and distributed in a larger space than those of subjects with normal TMJs. The HA parameters that reflected the more irregular and more asymmetric mandibular movements were (1) the significantly larger maximum translation T_{max} along the HA, that indicates a more pronounced mediolateral mandibular deflection, and (2) the significantly larger maximum distance d_{CPmax} between HA and condyle. These increased values are likely to be explained by the unilateral change in condylar translation velocity and sudden change in the rotation-translation ratio accompanying the clicking sound, i.e. when the condyle overcomes the disc obstacle during opening and when it slides behind the disc during closing. This phenomenon has been reported in the literature for joints with anterior disc displacement with reduction, the joint condition of our patients (Isberg-Holm and Ivarsson, 1980; Heller and Palla, 1988; Ernst, 1988). The unilateral change in condylar translation velocity produces a transiently asymmetric condylar motion during jaw opening/closing that causes the observed fluctuation and displacement of the HA. In support of this hypothesis is also the observation that the distance d_{CP} rapidly increases in the presence of condylar translation. Indeed, when the mandible opens in a retruded position, i.e. with a minimum amount of translation, the HA stays closer to the condyle than when it opens by a combination of rotation and translation (Gallo, 2000). This means that when the condylar translatory velocity increases, the distance d_{CP} must increase too. In summary, the HA is a very sensitive tool to detect a dyscoordination between rotation and translation as even a small translatory movement at a slow condylar rotation results in a substantial increase in the distance of the axis from the condyle.

The great sensitivity of the HA pathways to irregular mandibular movements is illustrated in Fig. 4 that shows opening/closing in a patient with a late opening and an early closing click. In this example, the HA suddenly loses its parallelism and starts swinging, a phenomenon more visible on closing than on opening. Thus, the HA pathways reflect irregularities in condylar movements likely better than the traces of single condylar points. As a matter of fact, if a condylar point of an asymptomatic TMJs is nonproperly chosen, its traces can show irregularities like those observed in clicking TMD (Peck et al., 1997; Morneburg and Proschel, 1998), whereas the HA model provides a comprehensive description of the movement of the mandible as a whole, independently form arbitrarily chosen points.

We recognize that a limitation of this study is the lack of a time correlation between clicking sound and sudden change in HA position and orientation. A further study that aims to correlate TMJ clicking and the degree of condylar acceleration with the HA pathways is planned with a new jaw tracking device, in development at our clinic, which has a better geometric resolution and higher data acquisition rate.

4.2. Mastication

Fig. 5 shows that the HA does not move parallel to itself during mastication as it does during opening/closing in subjects with normal TMJs. On the contrary, it shows a swing as it does during opening/closing in the presence of joints with reciprocal clicking. This HA behavior during mastication, already previously reported (Gallo et al., 2000), also reflects the different translatory velocity of the two condyles during chewing. The swing is more pronounced on closing than on opening as the difference in condylar translation and in the translation–rotation ratio between the two condyles is greater during this phase of the masticatory cycle. As a matter of fact, during closing the working condyle, i.e. the condyle on the side where the food is placed between the teeth, is retruded into the fossa and reaches its uppermost position far ahead of the opposite condyle, i.e. the balancing condyle (Gibbs et al., 1971). Also, while the balancing condyle is still translating posteriorly, the working condyle mostly rotates. Consequently, the HA moves in opposite directions on both sides as expressed by the decrease of the distance d_{CP} on the working side and its increase on the balancing side: at the end of closing, the HA is close to the working condyle and far from the balancing condyle. The smaller swing during opening than during closing, and therefore the smaller HA fluctuation, are due to the fact that the asymmetry in translation between the two condyles is less pronounced during this phase of the masticatory cycle.

The behavior of the HA parameters θ_x, θ_z, $x_{d\mathrm{CP}}$, $z_{d\mathrm{CP}}$ and d_{CP} differed significantly between mastication of bread, apple and cheese on one side and of dried meat and chewing gum on the other side. This may be due to the different rheological properties of these two groups of foods. As a matter of fact, dried meet is less brittle, more elastic and therefore tougher to chew than bread, apple and cheese, and chewing gum has quite different rheological properties than regular food: once it has been softened it keeps its consistency and is not comminuted to smaller particles. The finding that the rheological properties of the food influence some of the HA parameters seems concordant (1) with the observation that food hardness and size influence mandibular movements in so far that mandibular excursion increases with the bolus size (Daet et al., 1995; Miyawaki et al., 2000; Haggman-Henrikson and Eriksson, 2004) and possibly with the bolus hardness (Peyron et al., 2002; Anderson et al., 2002), and (2) that chewing of harder food leads to a wider chewing cycle and to a more dorsal closing path of the working side condyle (Gibbs et al., 1981; Gibbs et al., 1982; Nakajima et al., 2001; Anderson et al., 2002; Komiyama et al., 2003). Furthermore, an intraindividual increase of the excursion of HA oscillations and displacements was observed for larger than for smaller foods in over 87% of the recordings, which can be explained with the increase in opening and therefore the greater condylar translation and rotation needed to chew food of larger size.

The results of this study can be compared only to our previous ones (Gallo et al. 2000) as, to our knowledge, the HA behavior during mastication has not been analyzed by other research groups. Previous kinematic studies on mastication analyzed either the path of a single mandibular point, for instance the incisal or gnathion (Jemt et al., 1979; Häggman-Henrikson et al., 1998; Filipic and Keros, 2002; Haggman-Henrikson and Eriksson, 2004), or of several mandibular points simultaneously (Gibbs et al., 1971; Gibbs et al., 1981; Gibbs et al., 1982; Miyawaki et al., 2000; Miyawaki et al., 2001; Nakajima et al., 2001), or of a condylar point, such as the kinematic center (Naeije and Hofman, 2003). One of the limitations of the single point analysis is that it is very sensitive to the choice of its coordinates. Thus, in order to analyze changes in the path of single points over time it is necessary to always retrieve the same coordinates, a not so trivial issue. The HA analysis is on the other hand coordinates independent and therefore more suitable for follow-up recordings.

5. Conclusion

In conclusion, the helical axis pathways fluctuated more and moved in a larger space in subjects with TMJ clicking than in those with normal TMJs. Furthermore, they were influenced by the rheological quality of the food and its size. This study showed therefore that the helical axis pathway very sensitively reflects differences in the movement of both condyles.

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