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Analyzing center of rotation during opening and closing movements of the mandible using computer simulations

Sug-Joon Ahn [a], Ling Tsou [b], C. Antonio Sánchez [b], Sidney Fels [b], Ho-Beom Kwon [c,*]

[a] Dental Research Institute and Department of Orthodontics, School of Dentistry, Seoul National University, Seoul, Korea
[b] Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC, Canada
[c] Dental Research Institute and Department of Prosthodontics, School of Dentistry, Seoul National University, Seoul, Korea

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ABSTRACT

The traditional hinge axis theory for guiding clinical procedures in dentistry and dental articulators has been challenged by the concept of an instantaneous center of rotation (ICR), which is becoming more prevalent in modern explanations of mandibular movement. The purpose of this study was to analyze traditional hinge axis theory using three-dimensional computer simulations and to compare it with ICR. Three-dimensional computational models that reproduced the traditional pantograph tracing method were created to simulate the opening and closing movements of the jaw. Models of the bones, muscles and ligaments were combined to create a dynamic representation using ArtiSynth, a biomechanical simulation toolkit. The mandibular motion is constrained based on contact between the articular eminence and the mandibular condyle, and is limited by spring-like ligaments, as well as passive properties of the skeletal muscles. To estimate the center of rotation according to the traditional axis theory, markers on the pantograph were traced during mandibular opening and closing movement. The ICR was computed at each time step throughout the simulation. To locate a single hinge axis in simulation, the point about which the mandible seems to rotate during early opening and terminal closing was determined. The estimated center of rotation was inconsistent with the ICR, yet motion was found to be well approximated by a pure rotation. The inconsistency suggests that the use of the ICR position for the clinical dental procedures has its limitations.

1. Introduction

According to the hinge axis theory, the hinge axis of the mandible, or transverse horizontal axis, is an imaginary line around which the mandible rotates within the sagittal plane (Lucia, 1960; Preston, 1979). In this theory, the early stage of opening and terminal phase of closing of the mandible are described as pure hinge movements, and the mandible rotates about the intercondylar axis (Lucia, 1960; Sloane, 1952). Prosthodontists have reported that pure rotation movement occurs, around which a definite transverse axis can be located (Granger, 1952; McCollum, 1960; Posselt, 1957). A method for locating the hinge axis has been described in detail, and this hinge axis became the basis for many clinical dental procedures (Lucia, 1960; McCollum, 1960; Preston, 1979). Important clinical rehabilitation procedures in prosthodontics have been designed around this concept. Semi-adjustable articulators, which are widely used in the current clinical field, have a single fixed intercondylar axis. According to the hinge axis theory, an increase or decrease in the occlusal vertical dimension is possible using a dental articulator without changing the centric relationship (McCollum, 1960). Many studies related to occlusion and the stomatognathic system were also based on hinge axis theory because of its wide acceptance (Ishigaki et al., 1989; Nagy et al., 2002; Piehslinger et al., 1991; Roth and Williams, 1996; Stern et al., 1988). Although there have been reports opposing the hinge axis theory, it was suggested that the apparatus and procedures were at fault rather than the concept of a single terminal hinge axis (Aull, 1963). In addition to the application in prosthodontics, the concept of the hinge axis is also important in orthodontics and orthognathic surgery (Lindauer et al., 1995). An inaccurate description of mandibular rotation can have profound effects on orthognathic surgical treatment planning and surgical outcomes, as well as the precision of appliances fabricated on dental articulators.

However, the validity of the hinge axis theory has not gone unchallenged. Several studies suggested that pure rotary movement does not occur, and there is no fixed center of rotation during mandibular movement (Hellsing et al., 1995; Koski, 1962; Torii, 1989). Mandibular movements have been analyzed in several ways (Gallo et al., 1997; Naeije and Hofman, 2003). One is by computing an

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[*] Corresponding author. Tel.: +82 2 2072 3816; fax: +82 2 2072 3860.
E-mail address: proskwon@snu.ac.kr (H.-B. Kwon).

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instantaneous center of rotation (ICR). In the 1970s, the concept of ICR was introduced to describe mandibular movement (Grant, 1973). The ICR describes the position about which an object seems to be rotating at a given instant in time (Chen, 1998). At any given moment, the linear velocity of the ICR is assumed to be zero, and the motion of the whole object revolves around a single point (Chen, 1998). The use of the ICR produced significantly different results from those obtained assuming a fixed axis of rotation, and the results using ICR were reported to be in better agreement with the known functions of the masticatory muscles (Grant, 1973). In studies that followed, it was reported that the position of the ICR dramatically changed throughout opening and closing of the jaw, and there was no evidence to suggest that the temporomandibular joint (TMJ) functioned as a simple hinge (Ferrario et al., 1996; Jinbao et al., 1988; McMillan et al., 1989). A study using a kinesiograph confirmed that hinge axis theory could not accurately explain mandibular movements, as a pure rotation did not occur around any single axis, and the position of the center of rotation changed (Ferrario et al., 1996).

Many current studies on the joints of mammals, including rabbits (Weijs et al., 1989), pigs (Sun, 2002), and primates (Terhune et al., 2011), as well as humans (Lindauer et al., 1995; Yatabe et al., 1997), seem to have replaced the traditional hinge axis model with one based on the ICR. In addition, the use of ICR has been extended into diagnosis and treatment planning (Lupkiewicz et al., 1982). However, studies using ICR concept showed varied and inconsistent results with respect to the positions of the center of rotation (Chen and Katona, 1999; Jinbao et al., 1988). In some studies, ICRs have been reported to be scattered inferiorly and posteriorly to the condyles (Chen, 1998). However, in others studies, the center of rotation was estimated to pass through the mandible in some subjects (Smith, 1985). Jinbao et al. (1988) reported that the ICR could exist anywhere between the posterior border of the mandibular ramus and the mandibular neck, and other researchers concluded that it could even be located at variable distances and directions from the TMJ, producing different open–close patterns (Koolstra and van Eijden, 1997; McMillan and McMillan, 1986; McMillan et al., 1989). Overall, there is a lack of consistency between the ICR locations determined in these studies.

Although various methods have been used to analyze the center of rotation of the mandible, including a photographic method (Chick, 1960), radiographic methods (Hellsing et al., 1995; Jinbao et al., 1988), mechanical modeling (Baragar and Osborn, 1984), a graphical method (McMillan et al., 1989), and computer simulation (Chen and Katona, 1999; Koolstra and van Eijden, 1997), there seems to be no consistent and reliable technique for the investigation of the center of rotation. Recently, computer simulations are becoming important in basic studies related to the stomatognathic system and its clinical applications including treatment planning and diagnosis (Hannam et al., 2010; Pai, 2010; Peck et al., 2000). In simulation, many errors related to clinical methodology and human error can be eliminated (Rekow et al., 1993).

The purpose of this study was to reproduce mandibular opening and closing movements using three-dimensional (3D) computer simulations and to analyze the traditional hinge axis theory and the ICR projected onto the two-dimensional (2D) mid-sagittal plane.

2. Materials and methods

2.1. Model construction

A 3D computational model was created to simulate both opening and closing movements of the mandible. Geometries were obtained from computed tomography (CT) data using the image processing software AMIRA (Visage Imaging, Carlsbad, CA, USA). CT scans of a healthy 30-year-old male volunteer at a resting position were used. This subject fit all inclusion/exclusion criteria: a healthy young subject who had all dentition; no skeletal or dental anomalies; no experience with prosthodontic treatment, orthodontic treatment or maxillofacial surgery, and no history of temporomandibular disease, including internal derangement of discs. The geometries from the raw CT data were exported, and meshes were generated using the meshing program Visual-Crash (ESI Group, Paris, France). These meshes were then imported into ArtiSynth (University of British Columbia, Vancouver, Canada), a 3D biomechanical physics-based modeling platform for maxillofacial and airway research (Hannam et al., 2010; Stavness et al., 2010). The protocols and procedures of the study were reviewed and approved by the Institutional Review Board at Seoul National University Dental Hospital.

The model consists of the maxilla, the mandible, the hyoid bone, line muscles and spring ligaments. Bones were set as completely rigid structures. The mandible was actuated by 12 pairs of point-to-point Hill-type muscles (Zajac, 1989). These muscle models produce passive forces proportional to muscle stretches and active forces proportional to muscle activation (Langenbach and Hannam, 1999; Zajac, 1989). The muscles and their magnitudes of maximum muscle forces are shown in Table 1 (Hannam et al., 2008; Korioth and Hannam, 1994). To limit the mandibular motion, simple springs simulating ligaments were added (Osborn, 1989, 1993). The mandibular condyles directly contacted the articulating fossa of the maxilla (Baragar and Osborn, 1984). A rigid body collision was set between the maxilla and mandible, including the teeth. A rigid body simulating a pantograph was created to reproduce the clinical hinge axis tracing procedure (McCollum, 1960). The pantograph was connected to the mandible and moved simultaneously along with it, affecting the inertia, as well as resulting motion, of the system. The pantograph provided reference planes for tracking point motion. It had two recording tables, measuring 40 mm in height and length, parallel to the mid-sagittal plane and positioned based on the subject's face shape (Razek, 1981). On the recording plate, markers were attached at 5-mm intervals. Additional markers for tracing the motion of the mandible were attached on the incisal tips of the maxillary and mandibular central incisors. The final models are shown in Fig. 1. Note that in this model, there is no simple joint constraint between mandible and maxilla. Instead, the motion is constrained based on contact between the articular eminence and the mandibular condyle, and is limited by spring-like ligaments, as well as passive properties of the skeletal muscles. These constraints on the condyles are more similar to a real condyle motion.

2.2. Opening and closing movements of the mandible

In the ArtiSynth platform, the models were subjected to a gravitational field of $9.8\ \mathrm{m/s^2}$. The opening and closing movements of the mandible were performed by

Table 1
Magnitude of maximum muscle forces.

Muscle	Maximum force (N)
Superficial masseter	190.4
Deep masseter	81.6
Medial pterygoid	174.8
Anterior temporalis	158
Middle temporalis	95.6
Posterior temporalis	75.6
Inferior lateral pterygoid	66.9
Superior lateral pterygoid	28.7
Anterior digastric	40.0
Anterior mylohyoid	20.0
Posterior mylohyoid	20.0

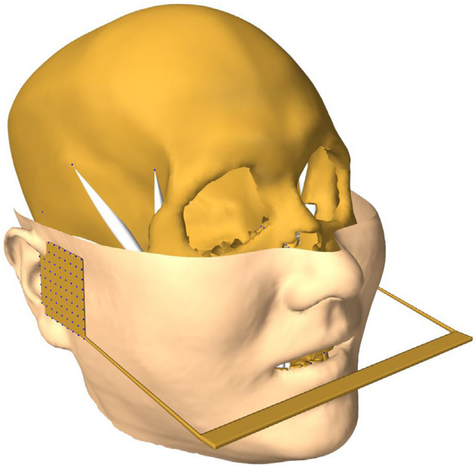

Fig. 1. Final model for simulation. A pantograph-like device was attached to the mandible.