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Functional Analysis of the Rabbit Temporomandibular Joint Using Dynamic Biplane Imaging

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Abstract

The dynamic function of the rabbit temporomandibular joint (TMJ) was analyzed through non-invasive three-dimensional skeletal kinematics, providing essential knowledge for understanding normal joint motion. The objective of this study was to evaluate and determine repeatable measurements of rabbit TMJ kinematics. Maximal distances, as well as paths were traced and analyzed for the incisors and for the condyle-fossa relationship. From one rabbit to another, the rotations and translations of both the incisors and the condyle relative to the fossa contained multiple clear, repeatable patterns. The slope of the superior/inferior incisor distance with respect to the rotation about the transverse axis was repeatable to 0.14 mm/degree and the right/left incisor distance with respect to the rotation about the vertical axis was repeatable to 0.03 mm/degree. The slope of the superior/inferior condylar translation with respect to the rotational movement about the transverse axis showed a consistent relationship to within 0.05 mm/degree. The maximal translations of the incisors and condyles were also consistent within and between rabbits. With an understanding of the normal mechanics of the TMJ, kinematics can be used to compare and understand TMJ injury and degeneration models.

Keywords

temporomandibular joint; 3D joint kinematics

INTRODUCTION

Some estimates suggest that over ten million Americans are affected by temporomandibular joint (TMJ) disorders (TMDs) (NIH and NIDCR, 2010). Clinical symptoms of TMDs

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Conflict of Interest Statement

The authors have no conflicts of interest to disclose.

include jaw locking, clicking, headaches, joint pain and tenderness, restricted range of motion, painful mastication, and deterioration of the disc and the articulating surfaces of the TMJ (Wilkes, 1989). Clinical exams often used to diagnose TMDs only test the end positions of the teeth and do not focus on the travel path of the joint. It is important to understand the kinematics of the joint to determine if early changes in the function of the joint may suggest oncoming TMDs.

Knowledge of dynamic TMJ function through three-dimensional (3D) skeletal kinematics is essential for understanding normal joint behavior and investigating the effects of injury or disease in the TMJ. Many factors contribute to joint motion including muscular forces, passive structures constricting movement, and dynamic physical forces such as contact, gravity and inertia (Markolf et al., 1981; Schipplein and Andriacchi, 1991). However, little is known on how these factors combine for everyday movement, making replication of kinematics difficult (Tashman and Anderst, 2003). 3D visualization and measurement techniques are necessary to measure skeletal kinematics with high precision and accuracy.

Various kinematic studies have been performed on humans, many looking at the effects of partial and total joint replacement and other invasive treatments on joint motions (Baltali et al., 2008; Gallo, 2005; Keller et al., 2012; Leiggener et al., 2012; Linsen et al., 2012; Palla et al., 2003; Voiner et al., 2011; Yoon et al., 2007). While incisal movement alone is not enough to understand the movement of the mandibular condyles (Naeije, 2002; Travers et al., 2000), 3D jaw tracking systems have provided more insight into condylar motion (Baltali et al., 2008; Gallo, 2005; Keller et al., 2012; Leiggener et al., 2012; Linsen et al., 2012; Palla et al., 2003; Voiner et al., 2011). In-depth TMD patient studies have not been performed with these systems because it is hard to identify patients at early stages of dysfunction. The current 3D systems are beneficial for human patient studies, but cannot be implemented in non-compliant animal models.

Animal studies are uniquely suited for investigating the disease initiation and progression that cannot be completed and repeated in a patient study, by enabling both mechanical interventions that may drive disease development and comprehensive, invasive tissue assessment. In particular the rabbit model was chosen due to the various TMJ injury and degeneration models already established in the literature (Ali and Sharawy, 1995; Almarza et al., 2011; Axelsson et al., 1992; Chaves et al., 2002; Shaw and Molyneux, 1993; Timmis et al., 1986; Tominaga et al., 1999; Tominaga et al., 2000; Ueki et al., 2003). Rabbits also exhibit a grinding mastication similar to that of humans (Morita et al., 2008). Several studies have previously collected normal rabbit kinematics; however, most done were invasively and only focused on incisal movement (Huff et al., 2004; Inoue et al., 2004; Inoue et al., 1989; Langenbach et al., 2001; Morimoto et al., 1985; Schwartz et al., 1989; Tominaga et al., 2000; Weijs et al., 1989a; Weijs and Dantuma, 1980; Weijs et al., 1989b; Yamada and Haraguchi, 1995; Yamada et al., 1988; Yamada et al., 1990), instead of also understanding condylar movement (Morita et al., 2008).

Non-invasive 3D x-ray imaging systems have been developed to combine x-ray videos with 3D morphology from bone scans and have been extensively validated in human and animal joints (Bey et al., 2008; Bey et al., 2006; Brainerd et al., 2010; Tashman and Anderst, 2003;

Tashman et al., 2007), including one study of normal minipig mastication (Brainerd et al., 2010). Our study investigated the dynamic nature of the TMJ condyle with respect to the fossa, as well as the incisor relationship in rabbits. The objective of this study was to determine and evaluate repeatable measurements of rabbit TMJ kinematics. The relative motion of the condyle with respect to the fossa was tracked. Maximal distances, as well as path, were traced and analyzed for the incisors and for the condyle-fossa relationship. By establishing kinematics for control animals, future kinematic assessments can be used to help understand the progression of specific TMDs.

METHODS

Animal Model

Three skeletally mature female New Zealand White rabbits, approximately 1 year in age, and weighing approximately 5kg, were purchased from Myrtle's Rabbitry Incorporated (Thompsons Station, TN). All rabbits were examined by a veterinarian and were found to be in good health. All animal procedures were approved by the Institutional Animal Care and Use Committee at the University of Pittsburgh, in accordance with the National Institutes of Health guidelines for the use of laboratory animals.

Measurement of TMJ Kinematics: High-Speed Biplane Radiography

TMJ kinematics were assessed using a unique high-speed stereo-radiographic system, consisting of two sets of 110kW pulsed x-ray generators (CPX 3100CV; EMD Technologies, Quebec, Canada), 40cm image intensifiers (Thales, Neuilly-sur-Seine, France) using a 20cm field of view, and high-speed 4 Megapixel digital video cameras (Phantom v10, Vision Research, Wayne, New Jersey, USA). The system configuration is shown in Figure 1. Data was collected at a frame rate of at least 170 frames/s for 1s with 4 Megapixel image resolution. Short-duration (1ms) exposures were performed to acquire images free of motion blur.

This system has been used extensively for studies of joint motion in humans and animals, with accuracy in the range of 0.07–0.3mm for a 40cm field of view (Craig et al., 2008; Tashman and Anderst, 2003; Tashman et al., 2007). For these rabbit studies, a 20cm field of view was used, reducing image pixel size by a factor of two with a concomitant increase in accuracy.

The rabbits were placed in a ventilated radiolucent cage (Figure 1). Small pieces of dried fruit were placed in the rabbit's mouth and radiographic images (Figure 2A) were acquired for a 1 second period. The process was repeated to collect at least three acquisitions per rabbit.

The model-based technique for determining 3D kinematics of skeletal structures from biplane radiographic views has been extensively described and validated. We have performed multiple in vivo and in vivo validations of our measurement methods for the knee, shoulder and cervical spine, by implanting beads on the bones (which can be tracked with high accuracy using well-established radio-stereometric techniques), and comparing this "gold standard" marker/bead tracking to the markerless tracking method employed for

this study (Anderst et al., 2009; Bey et al., 2006; Haque et al., 2013; Tashman and Anderst, 2003; You et al., 2001). Typical 3D measurement precision for these studies is in the order of 0.1–0.2mm during dynamic testing (and substantially better than 0.1mm for static imaging). Dynamic accuracy for joint kinematics (relative motion between two bones) was measured directly, and was typically around ± 0.5 mm for translations and ± 0.7 degrees for rotations. These are direct assessments of accuracy for clinically relevant measurements acquired at functionally relevant movement speeds that account for propagation of all sources of error.

In actuality, the accuracy for this rabbit TMJ study was substantially better. Under similar bone sizes and imaging conditions, TMJ tracking accuracy would equal or exceed that for the knee/shoulder, because there are more features and image details in the skull and mandible than there are for the knee or shoulder. The knee and shoulder validation studies were done with radiographic imaging resolution of approximately 0.5mm/pixel and CT slice spacing of 0.6 or 1.2mm (within-slice resolution of approximately 0.5mm). The rabbit jaw is much smaller, so a smaller field of view was employed; the images used for tracking had a pixel size of approximately 0.125mm. Head/jaw CT scans were obtained using a micro-CT system with isotropic, 0.1mm voxels. While we have not specifically assessed accuracy under these conditions, it is certain that better imaging resolution will improve tracking accuracy. We are conservatively estimating that this 400% improvement in radiographic image resolution, combined with a 500% (or better) improvement in CT scan resolution (along with the greater bone details inherent in the skull and mandible images), will result in a error reduction (relative to the shoulder/knee studies) of at least a factor of 2. Thus, we estimate that the accuracy for TMJ kinematics is approximately ± 0.2 mm in translation and ± 0.4 degrees in rotation. For the incisors, this 0.2mm error relates to 5% error in the differences in superior-inferior translations measured between rabbits. For the condyles, an error of 0.2mm results in a 15% error in the differences in superior-inferior translations measured between rabbits.

Briefly, a 3D model of each bone to be tracked was derived from a computed tomography (CT) scan (as described below). A virtual model of the biplane x-ray system was created for generating a pair of digitally reconstructed radiographs (DRR's) via ray-traced projection through the CT bone model. The bone model was automatically repositioned within the virtual model until a best match was achieved between the simulated DRR's and the actual radiographic image pair (Figure 2B,C). This technique determined the 3D positions and orientations of the mandible and the skull for each motion frame.

Bone Models from Micro-Computed Tomography

Accurate, animal-specific bone models were required for both model-based tracking and kinematic analysis. After euthanasia, the entire head, including the mandible and skull, was scanned at high resolution (102.5 μ m isotropic voxels) using a micro-computed tomography system (Inveon micro-CT system by Siemens at the Rangos Research Center Animal Imaging Core, Children's Hospital of Pittsburgh of UPMC). The mandible and skull bones (with teeth) were segmented from each other and from soft tissue and reconstructed into both surface and volumetric models using Mimics software (Materialise, Inc).

Coordinate Systems

Anatomical coordinate systems were set up similar to the systems used by Brainerd *et al.* (Brainerd et al., 2010). The transverse axis was aligned through the center of the condyles (or fossas for the skull), the longitudinal axis was parallel to the occlusal plane (where the molars meet) running posterior to anterior, and the vertical axis was the cross product of the transverse and longitudinal axes (Figure 3). The coordinate systems were centered between the condyles and fossas for the mandible and skull, respectively. The orientations of the anatomical coordinate systems were determined using standard rigid body transformations, and translations and rotations were determined. The joint rotations were calculated in the order of rotation about the transverse axis, rotation about the vertical axis, and rotation about the longitudinal axis.

Analysis of Biodynamics

Our analysis focused on the dynamic behavior of the TMJ rather than only the end of range displacement of the jaw. The center points on the incisors were tracked in all three planes (Figure 4A,B). The relative motion of the condyle in relation to the fossa was tracked by placing points at the most superior point of the condyle and in the concave region of the fossa (Figure 4E,F). The relative motion of the centers of the two points was determined in all three anatomic planes. These points were rigidly fixed and the position measured in each frame. A future study will need to determine the reliability of determining the coordinate planes.

For each animal, kinematics from at least three representative chewing cycles were analyzed from each of a minimum of three different acquisitions. Three acquisitions per rabbit were chosen based on the observation of three distinctive complete chewing cycles; one chewing cycle is equal to a full opening and closing of the mandible. One full chew cycle was determined on a time graph to be the distance or rotation from one peak to the next peak (Figure 5). Analyses were performed to determine the maximal translations and travel paths for both the incisors and the condyles.

Incisors-Maximal Translations—Motion of the incisors was described by quantification of their total displacement right/left, superior/inferior, and anterior/posterior during a chew cycle from peak displacements in each direction during each chew cycle (Figure 5A). Thus, three parameters of the contact point on the incisors were compared: 1) Maximal change in superior/inferior translation; 2) Maximum left/right translation; 3) Maximum anterior/posterior translation.

Incisors-Path—To describe path, each mandible rotation in the coordinate plane (Figure 5B) was compared to each incisor translation to identify any relationships that existed. The translation-rotation relationships analyzed were chosen when a repeatable linear pattern was observed, which allowed for the slope to be compared between different acquisitions. If no repeatable and/or linear pattern was observed, the slope was not calculated. The following slopes were chosen for analysis: 4) Slope of the superior/inferior translation of the incisors with respect to mandible rotation about the transverse axis (Figure 6A); 5) Slope of the left/

right translation of the incisors with respect to the mandible rotation about the vertical axis (Figure 6B).

Condyle-Maximal Translations—The movement of the mandible was somewhat elliptical in the coronal plane and always started to the same side during an acquisition. As established in the literature, the side in which the mandible first moves is the working side, while the other is called the balancing side (Morita et al., 2008). The total displacement for both the working side and balancing side condyles was measured. Total superior/inferior displacement was found by subtracting the maximal opening from the maximal closing of the mandible relative to the fossa during a chew cycle. Additionally, the total displacement anterior/posterior was calculated. The left to right condylar displacement was minimal. The following parameters were described: 6) Maximum working condyle superior/inferior translation relative to the fossa; 7) Maximum balancing condyle superior/inferior translation relative to the fossa; 8) Maximum working condyle anterior/posterior translation relative to the fossa; 9) Maximum balancing condyle anterior/posterior translation relative to the fossa.

Condyles-Path—The translations of the condyles were plotted with respect to the mandible rotations, and the relationships to be analyzed were chosen when a repeatable linear pattern was observed, which allowed for the slope to be compared between different acquisitions. If no repeatable and/or linear pattern was observed, that specific evaluation was not used. The analysis of the superior/inferior movement of the condyle relative to the fossa with respect to the rotation of the mandible about the transverse axis was performed according to the direction of chewing. Analysis depended on the side of mastication as well as the opening and closing of the mouth. The only repeatable behavior was seen in the superior/inferior translation of the condyles with respect to the transverse axis rotation of the mandible (Figure 7A,B). For this measure, a linear pattern was observed when analyzing the slope of only the first fifty percent of the closing cycle. Comparisons were made amongst the slopes calculated from the closing condyle cycle of the working and balancing sides of the mandible: 10) Slope of the working side superior/inferior translation of the condyle relative to the fossa with respect to the mandible rotation about the transverse axis; 11) Slope of the balancing side superior/inferior translation of the condyle relative to the fossa with respect to the mandible rotation about the transverse axis.

Statistical Analysis

In summary, first, to determine differences amongst chewing stage (opening and closing) for all biodynamics parameters for multiple chewing cycles a student t-test was performed. The data was found to have a normal distribution using the Anderson-Darling Test for Normality. Then, a one-way ANOVA (Minitab 16, State College, Pennsylvania, USA) with Tukey's post hoc testing was then used to assess differences for all biodynamics parameters amongst chewing cycles within individual acquisitions, amongst acquisitions within each rabbits, and amongst rabbits from at least three acquisitions. The data used for the ANOVAs was found to have a normal distribution using the Anderson-Darling Test for Normality. A statistically significant difference was established as $p < 0.05$. All data was reported as an average $\pm$ standard deviation of the mean.

In more detail, statistical analyses for all reported biodynamic variables were performed in four stages. Firstly, chewing stage (opening, closing) within a chewing cycle, for all chewing cycles, acquisitions, and rabbits were assumed to be different; however, no statistical significances were found and therefore the values for opening and closing for each chew cycle were averaged into one opening/closing value per cycle. Then secondly, all chewing cycles (at least three) within an acquisition, for all acquisitions and rabbits were assumed to be different; however, no statistical significance was found for the opening/closing value between chew cycles and hence the values of chew cycles for each acquisition were averaged into one chew cycle value per acquisition. Thirdly, acquisitions (at least three) for each rabbit, for all rabbits were assumed to be different; again, no statistically significant differences were observed. Thus, all biodynamic parameters are averaged into one acquisition value per rabbit. Fourthly, acquisitions between rabbits were assumed to be different; and in this case one rabbit was different than the other two, which did not allow for the data to be averaged for all rabbits.

RESULTS

Evaluation of the movement of the upper and lower incisors from opening to closing revealed a periodic pattern in all three directions and all three rotations (Figure 5). In the superior/inferior direction, the total incisor displacement was 9.03 ± 1.55 mm for Rabbit 2, which was statistically different from the other two rabbits with an average displacement of 14.55 ± 3.71 mm ($p < 0.05$, for details see Table 1). The total displacement, between the upper and lower incisors in the right/left direction was statistically different for Rabbit 2 with a distance of 3.70 ± 1.11 mm compared to the average of other two rabbits at 6.58 ± 1.09 mm ($p < 0.05$, Table 1). In the anterior/posterior direction, the maximum displacement was significantly different between Rabbits 1 (4.99 ± 1.13 mm) and 2 (1.82 ± 0.43 mm), but neither were different from Rabbit 3 (3.20 ± 0.86 mm) ($p < 0.05$, Table 1).

Repeatable measurable relationships (Figure 6) were found by determining the slopes of the incisor displacement in the superior/inferior direction with respect to the rotation of the mandible about the transverse axis curves. Rabbit 2 (1.33 ± 0.04 mm/degree) was statistically different from Rabbits 1 and 3 (1.19 ± 0.03 mm/degree) for the slope of the superior/inferior displacement with respect to rotation about the transverse axis ($p < 0.05$). The slopes of the incisor displacement right/left with respect to the rotation of the mandible about the vertical axis curves were also repeatable with an average of -1.38 ± 0.06 mm/degree with no statistical differences between rabbits ($p < 0.05$, Table 1).

Comparison of the distance of the condyles of the mandible from the fossas in the superior/inferior, right/left, and anterior/posterior directions with respect to the rotation around the transverse axis, longitudinal axis, and vertical axis showed various discernible patterns. The superior/inferior displacement of the working condyle showed that Rabbit 2 and 3 had an average displacement of 1.59 ± 0.25 mm where as Rabbit 1 had a statistically different total displacement of 2.42 ± 0.18 mm (Table 1). Similarly, an analysis for displacement superior/inferior of the balancing condyle showed that Rabbit 2 and 3 had an average displacement of 1.43 ± 0.09 mm where as Rabbit 1 had a significantly different displacement of 1.95 ± 0.18 mm (Table 1). Between rabbits, the average working condyle displacement anterior/posterior

was 4.57 ± 1.24 mm and the average balancing condyle displacement anterior/posterior was 4.07 ± 0.48 mm (Table 1). Neither parameter showed statistically significant differences amongst the rabbits. The right/left condylar displacement was generally less than 0.5 mm and did not follow a consistent pattern and was not compared.

The relationship between the distance superior/inferior with respect to the rotation around the transverse axis of the condyle relative to the fossa created a repeatable pattern for both the chewing and balancing condyle (Figure 7). All other relationships showed neither a linear nor consistent repeatable pattern. Within rabbits, the slope of the closing cycle of the working condyle slope averaged was 0.21 ± 0.04 mm/degree with no statistical differences between rabbits (Table 1). The closing cycle of the balancing condyle slope was 0.14 ± 0.01 mm/degree for Rabbit 2, which was statistically different from the other two rabbits with a value of 0.09 ± 0.02 mm/degree ($p < 0.05$). The slope of the condyle on the working side as the mouth closed was roughly two times larger than the slope of the condyle on the balancing side ($p < 0.05$).

DISCUSSION

The characterization of the kinematic masticatory patterns of the rabbit is important in understanding the normal movement of the TMJ. The normal mechanics of the TMJ can be used to compare and distinguish kinematics of injured/degenerated joints, as well as healing joints. Our results demonstrate that from one rabbit to another the rotation and translation of both the incisors and the condyle movement relative to the fossa contain many clear, repeatable patterns. Specifically, for the incisors, the slope of the superior/inferior distance with respect to the rotation about transverse axis was repeatable to 0.14 mm/degree and the right/left distance with respect to the rotation about the vertical axis was repeatable to 0.03 mm/degree. For the condyles the slope of the superior/inferior translation with respect to the rotational movement about the transverse axis showed a consistent relationship within trials of each rabbits and between all of the rabbits to within 0.05 mm/degree. Furthermore, the maximal translations of the incisors and condyles were also consistent within rabbits and between rabbits. Some differences between the individual rabbits were expected, due to the natural variations between rabbits.

Previous studies have used various methods of recording rabbit jaw kinematics including magnetic sensing systems, photoelectric sensing systems, cineradiographic systems and video recording systems (Huff et al., 2004; Inoue et al., 2004; Inoue et al., 1989; Langenbach et al., 2001; Morimoto et al., 1985; Morita et al., 2008; Schwartz et al., 1989; Tominaga et al., 2000; Weijs et al., 1989a; Weijs and Dantuma, 1980; Weijs et al., 1989b; Yamada and Haraguchi, 1995; Yamada et al., 1988; Yamada et al., 1990). These studies were all invasive with the placement of bone markers, sensors, magnets, and screws. Comparing our results to previous rabbit kinematic studies showed that our study yielded similar findings. In several studies, the chewing patterns were studied by affixing a magnet to the mandible and a magnetic sensor to the skull and the voltage differences were measured (Inoue et al., 2004; Langenbach et al., 2001; Morita et al., 2008; Tominaga et al., 2000; Yamada and Haraguchi, 1995; Yamada et al., 1988; Yamada et al., 1990). The general paths and patterns of the incisors in the vertical and horizontal directions were similar to

what we observed (Figure 8), but numerical comparison was not possible, due to the measurement techniques. Similar chewing patterns were also seen with the photoelectric sensing systems (Inoue et al., 1989; Morimoto et al., 1985; Schwartz et al., 1989). The cineradiographic studies allowed for comparisons of the rotations about the transverse axis, similar rotations were found generally ranging from approximately 10–14° (Weijs et al., 1989a; Weijs and Dantuma, 1980; Weijs et al., 1989b). Another study found similar results for the incisal movement as rabbit study using 3D video analysis with skin markers during mastication of food and water (Huff et al., 2004). The superior/inferior displacement with food was roughly 13.1 ± 3.0 mm compared to our average between the three rabbits being 12.7 ± 3.7 mm. However, unlike our results the right/left movement recorded was larger with a mean of 17.6 ± 3.0 mm as opposed to our mean of 5.54 ± 1.70 mm, which was closer to their mean for the water stimulus (3.6 ± 0.5 mm) (Huff et al., 2004). The difference may arise from the variability that arises from the use of skin markers and the type of food stimulus.

One rabbit research study measured the mandibular condylar movement during mastication (Morita et al., 2008). The measurements were invasively done by removing the zygomatic arch and recording the motion of the condyles with a video camera on anaesthetized rabbits. Similar working side and balancing side path patterns for the motion of the condyles to our paths (Figure 9) were found. The incisor paths were also similar and recorded by magnetic sensors.

The dynamic biplane x-ray imaging system we used was beneficial because it allowed for non-invasive measurement of normal rabbit chewing, both at the incisors and within the joint space. In the future, our system can be used to determine kinematic differences and changes over time in chewing patterns between healthy and degenerated joints in animal models. Gaining a better understanding of the current models used for TMD and the fibrocartilage degeneration process, will allow for development of more appropriate models to better understand TMDs. Based on evidence that TMJ degeneration and pain results in alterations in oral-motor patterns, we hypothesize that kinematic analysis will identify a specific pattern of use-dependent changes in joint function that constitute a signature for the presence of permanent degeneration and pain. This will be studied in the future through the use of a mechanical induction of TMJ degeneration using unilateral dental splints.

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REFERENCES

- Ali AM, Sharawy MM. Alteration in fibronectin of the rabbit craniomandibular joint tissues following surgical induction of anterior disk displacement: Immunohistochemical study. *Acta Anatomica*. 1995; 152:49–55. [PubMed: 7604678]
- Almarza AJ, Hagandora CK, Henderson SE. Animal models of temporomandibular joint disorders: Implications for tissue engineering approaches. *Annals of Biomedical Engineering*. 2011; 39:2479–2490. [PubMed: 21822741]

- Anderst W, Zuel R, Bishop J, Demps E, Tashman S. Validation of three-dimensional model-based tibio-femoral tracking during running. *Medical Engineering & Physics*. 2009; 31:10–16. [PubMed: 18434230]
- Axelsson S, Holmlund A, Hjerpe A. An experimental model of osteoarthritis in the temporomandibular joint of the rabbit. *Acta Odontologica Scandinavica*. 1992; 50:273–280. [PubMed: 1441931]
- Baltali E, Zhao KD, Koff MF, Durmu E, An KN, Keller EE. Kinematic Assessment of the Temporomandibular Joint Before and After Partial Metal Fossa Eminence Replacement Surgery: A Prospective Study. *Journal of Oral and Maxillofacial Surgery*. 2008; 66:1383–1389. [PubMed: 18571021]
- Bey MJ, Kline SK, Tashman S, Zuel R. Accuracy of biplane x-ray imaging combined with model-based tracking for measuring in-vivo patellofemoral joint motion. *Journal of Orthopaedic Surgery and Research*. 2008; 3
- Bey MJ, Zuel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. *Journal of Biomechanical Engineering*. 2006; 128:604–609. [PubMed: 16813452]
- Brainerd EL, Baier DB, Gatesy SM, Hedrick TL, Metzger KA, Gilbert SL, Crisco JJ. X-Ray reconstruction of moving morphology (XROMM): Precision, accuracy and applications in comparative biomechanics research. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*. 2010; 313 A:262–279.
- Chaves K, Munerato MC, Ligocki A, Lauxen I, De Quadros OF. Microscopic Analysis of the Temporomandibular Joint in Rabbits (*Oryctolagus cuniculus* L.) Using An Occlusal Interference. *Cranio*. 2002; 20:116–124. [PubMed: 12002827]
- Craig M, Bir C, Viano D, Tashman S. Biomechanical response of the human mandible to impacts of the chin. *Journal of Biomechanics*. 2008; 41:2972–2980. [PubMed: 18805529]
- Gallo LM. Modeling of Temporomandibular Joint Function Using MRI and Jaw-Tracking Technologies -- Mechanics. In: Karger, AG., editor. *Cells Tissues Organs*. 2005. p. 54–68.
- Haque MA, Anderst W, Tashman S, Marai GE. Hierarchical model-based tracking of cervical vertebrae from dynamic biplane radiographs. *Medical Engineering and Physics*. 2013; 35:994–1004. [PubMed: 23122602]
- Huff KD, Asaka Y, Griffin AL, Berg WP, Seager MA, Berry SD. Differential mastication kinematics of the rabbit in response to food and water: Implications for conditioned movement. *Integrative Physiological and Behavioral Science*. 2004; 39:16–23. [PubMed: 15379379]
- Inoue M, Harasawa Y, Yamamura K, Ariyasinghe S, Yamada Y. Effects of food consistency on the pattern of extrinsic tongue muscle activities during mastication in freely moving rabbits. *Neuroscience Letters*. 2004; 368:192–196. [PubMed: 15351447]
- Inoue T, Kato T, Masuda Y, Nakamura T, Kawamura Y, Morimoto T. Modifications of masticatory behavior after trigeminal deafferentation in the rabbit. *Experimental Brain Research*. 1989; 74:579–591. [PubMed: 2707333]
- Keller EE, Baltali E, Liang X, Zhao K, Huebner M, An KN. Temporomandibular custom hemijoint replacement prosthesis: Prospective clinical and kinematic study. *Journal of Oral and Maxillofacial Surgery*. 2012; 70:276–288. [PubMed: 21856060]
- Langenbach GEJ, Weijs WA, Brugman P, Van Eijden TMGJ. A longitudinal electromyographic study of the postnatal maturation of mastication in the rabbit. *Archives of Oral Biology*. 2001; 46:811–820. [PubMed: 11420053]
- Leiggener CS, Erni S, Gallo LM. Novel approach to the study of jaw kinematics in an alloplastic TMJ reconstruction. *International Journal of Oral and Maxillofacial Surgery*. 2012; 41:1041–1045. [PubMed: 22819692]
- Linsen SS, Reich RH, Teschke M. Mandibular kinematics in patients with alloplastic total temporomandibular joint replacementa prospective study. *Journal of Oral and Maxillofacial Surgery*. 2012; 70:2057–2064. [PubMed: 22907108]
- Markolf KL, Bargar WL, Shoemaker SC, Amstutz HC. The role of joint load in knee stability. *Journal of Bone and Joint Surgery - Series A*. 1981; 63:570–585.

- Morimoto T, Inoue T, Nakamura T, Kawamura Y. Characteristics of rhythmic jaw movements of the rabbit. *Archives of Oral Biology*. 1985; 30:673–677. [PubMed: 3865644]
- Morita T, Fujiwara T, Negoro T, Kurata C, Maruo H, Kurita K, Goto S, Hiraba K. Movement of the mandibular condyle and activity of the masseter and lateral pterygoid muscles during masticatory-like jaw movements induced by electrical stimulation of the cortical masticatory area of rabbits. *Archives of Oral Biology*. 2008; 53:462–477. [PubMed: 18243158]
- Naeije M. Local kinematic and anthropometric factors related to the maximum mouth opening in healthy individuals. *Journal of Oral Rehabilitation*. 2002; 29:534–539. [PubMed: 12071921]
- NIH, NIDCR. TMJ Disorders. 2010
- Palla S, Gallo LM, Gössi D. Dynamic stereometry of the temporomandibular joint. *Orthodontics & Craniofacial Research*. 2003; 6(Suppl 1):37–47. [PubMed: 14606533]
- Schipplein OD, Andriacchi TP. Interaction between active and passive knee stabilizers during level walking. *Journal of Orthopaedic Research*. 1991; 9:113–119. [PubMed: 1984041]
- Schwartz G, Enomoto S, Valiquette C, Lund JP. Mastication in the rabbit: A description of movement and muscle activity. *Journal of Neurophysiology*. 1989; 62:273–287. [PubMed: 2754478]
- Shaw RM, Molyneux GS. The effects of induced dental malocclusion on the fibrocartilage disc of the adult rabbit temporomandibular joint. *Archives of Oral Biology*. 1993; 38:415–422. [PubMed: 8328922]
- Tashman S, Anderst WJ. In-vivo measurement of dynamic joint motion using high speed biplane radiography and CT: application to canine ACL deficiency. *Journal of Biomechanical Engineering*. 2003; 125:238–245. [PubMed: 12751286]
- Tashman S, Kolowich P, Collon D, Anderson K, Anderst WJ. Dynamic Function of the ACL-reconstructed Knee during Running. *Clinical Orthopaedics and Related Research*. 2007; 454:66–73. [PubMed: 17091011]
- Timmis DP, Aragon SB, Van Sickels JE, Aufdemorte TB. Comparative study of alloplastic materials for temporomandibular joint disc replacement in rabbits. *Journal of Oral and Maxillofacial Surgery*. 1986; 44:541–554. [PubMed: 3522828]
- Tominaga K, Alstergren P, Kurita H, Kopp S. Serotonin in an antigen-induced arthritis of the rabbit temporomandibular joint. *Archives of Oral Biology*. 1999; 44:595–601. [PubMed: 10414874]
- Tominaga K, Yamada Y, Fukuda J. Changes in chewing pattern after surgically induced disc displacement in the rabbit temporomandibular joint. *Journal of Oral and Maxillofacial Surgery*. 2000; 58:400–405. [PubMed: 10759120]
- Travers KH, Buschang PH, Hayasaki H, Throckmorton GS. Associations between incisor and mandibular condylar movements during maximum mouth opening in humans. *Archives of Oral Biology*. 2000; 45:267–275. [PubMed: 10708667]
- Ueki K, Takazakura D, Marukawa K, Shimada M, Nakagawa K, Takatsuka S, Yamamoto E. The use of polylactic acid/polyglycolic acid copolymer and gelatin sponge complex containing human recombinant bone morphogenetic protein-2 following condylectomy in rabbits. *Journal of Cranio-Maxillofacial Surgery*. 2003; 31:107–114. [PubMed: 12628601]
- Voiner J, Yu J, Deitrich P, Chafin C, Giannakopoulos H. Analysis of mandibular motion following unilateral and bilateral alloplastic TMJ reconstruction. *International Journal of Oral and Maxillofacial Surgery*. 2011; 40:569–571. [PubMed: 21376536]
- Weijjs WA, Brugman P, Grimbergen CA. Jaw movements and muscle activity during mastication in growing rabbits. *Anatomical Record*. 1989a; 224:407–416. [PubMed: 2782624]
- Weijjs WA, Dantuma R. Functional anatomy of the masticatory apparatus in the rabbit (*Oryctolagus cuniculus* L.). *Netherlands Journal of Zoology*. 1980; 31:99–147.
- Weijjs WA, Korfage JAM, Langenbach GJ. The functional significance of the position of the centre of rotation for jaw opening and closing in the rabbit. *Journal of Anatomy*. 1989b; 162:133–148. [PubMed: 2808111]
- Wilkes CH. Internal derangements of the temporomandibular joint. Pathological variations. *Archives of Otolaryngology - Head and Neck Surgery*. 1989; 115:469–477. [PubMed: 2923691]
- Yamada Y, Haraguchi N. Reflex changes in the masticatory muscles with load perturbations during chewing hard and soft food. *Brain Research*. 1995; 669:86–92. [PubMed: 7712169]

- Yamada Y, Haraguchi N, Oi K, Sasaki M. Two-dimensional jaw tracking and EMG recording system implanted in the freely moving rabbit. *Journal of Neuroscience Methods*. 1988; 23:257–261. [PubMed: 3367662]
- Yamada Y, Uchida K, Sato T. Mandibular movement trajectories and masticatory muscle activities in the rabbit in the sleep and wake states. *Dentistry in Japan*. 1990; 27:35–39. [PubMed: 2099289]
- Yoon HJ, Baltali E, Zhao KD, Rebellato J, Kademani D, An KN, Keller EE. Kinematic Study of the Temporomandibular Joint in Normal Subjects and Patients Following Unilateral Temporomandibular Joint Arthrotomy With Metal Fossa-Eminence Partial Joint Replacement. *Journal of Oral and Maxillofacial Surgery*. 2007; 65:1569–1576. [PubMed: 17656285]
- You BM, Siy P, Anderst W, Tashman S. In vivo measurement of 3-D skeletal kinematics from sequences of biplane radiographs: Application to knee kinematics. *IEEE Transactions on Medical Imaging*. 2001; 20:514–525. [PubMed: 11437111]

X-ray Generators

Image Intensifiers
and High Speed
Cameras

Figure 1.

High-speed biplane radiography was used for image collection. Rabbits were placed in a radiolucent box between two sets of x-ray generators and image intensifiers with high speed cameras.

Figure 2.

Sample x-ray image from the high resolution cameras at one frame in time (A). For 2D to 3D registration, the collected x-ray images (pink) are matched frame by frame with the virtual x-ray images (green) from the CT scan. One of the two combined images is shown for each the mandible (B) and the skull (C).

Figure 3.

The anatomical coordinate system for the mandible (A) was set up with the transverse axis (x-red) was aligned through the center of the condyles, the longitudinal axis (y-green) was parallel to a plane through the occlusal plane (where the teeth meet), and the vertical axis (z-blue) was the cross product of the transverse and longitudinal axes. The skull coordinate system was set up in a similar manner (B). The coordinate systems were centered between the condyles and fossas, for the mandible and skull respectively.

Figure 4.

Points placed for measurements. (A) Mandible incisor point, superior view (B) Skull incisor point, anterior view. (C) Vector demonstrating the distance between the incisor points. (E) Condylar point, anterior view. (F) Fossa point, inferior view. (G) Vector indicating the distance between the condylar point and the fossa point (condyle is labeled with C and the fossa with F).

Figures are labeled by directions: A-anterior, P-posterior, M-medial, L-lateral, S-superior, I-inferior.

Figure 5.

A.) The change in distance of the mandible incisors from the skull incisors with relation to time. B.) The change in the rotation of the mandible around the vertical, transverse and longitudinal axes with relation to time. One chew cycle is considered to be from one peak to the adjacent peak. Representative data shown.

Figure 6.

Comparison of the distance of the mandible incisors from the skull incisors with respect to the rotation of the mandible. (A.) The distance traveled superior/inferior with respect to the rotation of the mandible around the transverse axis. (B.) The distance traveled right/left with respect to the rotation of the mandible around vertical axis. Representative data shown.

Figure 7.

Comparison of the distance of the condyle relative to the fossa with respect to the rotation of the mandible. The distance traveled superior/inferior with respect to the rotation of the mandible around the transverse axis of the working side condyle (A.) and the balancing condyle (B.). At an angle of 0° the mouth is considered to be closed. The opening of the mouth translations are represented by the bottom line of the ellipse and the closing of the mouth translations are represented by the top line.

Representative data shown.

Figure 8.

Translation of the mandible incisors from the skull incisors in the coronal plane. The total movement superior/inferior with respect to right/left for three chewing cycles within one acquisition of one rabbit. Representative data shown.

A. Working Condyle **B. Balancing Condyle** **Figure 9.**

Condyle Distance - Translation of the condyle relative to the fossas in the sagittal plane. (A.) Total movement of the working side condyle superior/inferior with respect to right/left and (B.) total movement of the balancing side condyle superior/inferior with respect to right/left. The translations shown are for three continuous chewing cycles within one acquisition of one rabbit.

Representative data shown.

Table 1

Kinematic data sorted by consistent and variable measurements across rabbits including: total incisor displacements, slopes of incisor displacement with respect to rotations, total condyle displacement and slope of condyle displacements with respect to rotations for the working and balancing condyles. The average and standard deviation values are presented. Values are significant when $p < 0.05$.

	Rabbit 1	Rabbit 2	Rabbit 3
<i>Consistent Measurements</i>			
Slope of Incisor Distance Right/Left vs. Vertical Rotation	-1.39 $\pm$ 0.07	-1.42 $\pm$ 0.08	-1.39 $\pm$ 0.01
Total Working Condyle Displacement Anterior/Posterior	5.24 $\pm$ 0.73	3.20 $\pm$ 1.63	4.94 $\pm$ 0.36
Total Balancing Condyle Displacement Anterior/Posterior	4.35 $\pm$ 0.49	3.50 $\pm$ 0.05	4.18 $\pm$ 0.18
Slope of Working Condyle Distance Superior/Inferior vs. Transverse Rotation	0.23 $\pm$ 0.04	0.21 $\pm$ 0.02	0.18 $\pm$ 0.01
<i>Variable Measurements</i>			
Total Incisor Displacement Superior/Inferior	16.52 $\pm$ 2.12	9.03 $\pm$ 1.55 *	12.59 $\pm$ 4.28
Total Incisor Displacement Right/Left	7.03 $\pm$ 0.70	3.70 $\pm$ 1.11 *	5.90 $\pm$ 1.51
Total Incisor Displacement Anterior/Posterior	4.99 $\pm$ 1.13 ^	1.82 $\pm$ 0.43 ^	3.20 $\pm$ 0.86
Slope of Incisor Distance Superior/Inferior vs. Transverse Rotation	1.18 $\pm$ 0.03	1.33 $\pm$ 0.04 *	1.21 $\pm$ 0.01
Total Working Condyle Displacement Superior/Inferior	2.42 $\pm$ 0.18 *	1.46 $\pm$ 0.16	1.72 $\pm$ 0.31
Total Balancing Condyle Displacement Superior/Inferior	1.95 $\pm$ 0.18 *	1.50 $\pm$ 0.05	1.36 $\pm$ 0.01
Slope of Balancing Condyle Distance Superior/Inferior vs. Transverse Rotation	0.10 $\pm$ 0.01	0.14 $\pm$ 0.01 *	0.07 $\pm$ 0.01

* $p < 0.05$ when different from other two rabbits

^ $p < 0.05$ between rabbits with ^ but not with the third rabbit