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Development of a Mandibular Motion Simulator for Total Joint Replacement

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Abstract

Purpose—The purpose of this study was to develop a motion simulator capable of recreating and recording the full range of mandibular motions in a cadaveric preparation for an intact temporomandibular joint (TMJ) and after total joint replacement.

Material and Methods—A human cadaver head was used. Two sets of tracking balls were attached to the forehead and mandible, respectively. Computed tomographic (CT) scan was performed and 3-dimensional CT models of the skull were generated. The cadaver head was then dissected to attach the muscle activation cables and mounted onto the TMJ simulator. Realistic jaw motions were generated through the application of the following muscle forces: lateral

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pterygoid muscle, suprahyoid depressors (geniohyoid, mylohyoid, and digastric muscles), and elevator muscles. To simulate muscle contraction, cables were inserted into the mandible at the center area of each muscle's attachment. To provide a minimum mouth closing force at the initial position, the elevator muscles were combined at the anterior mandible. During mandibular movement, each motion was recorded using a high-resolution laser scanner. The right TMJ of the same head was reconstructed with a total TMJ prosthesis. The same forces were applied and the jaw motions were recorded again. CT scan was performed and 3-dimensional CT models of the skull with TMJ prosthesis were generated.

Results—Mandibular motions, before and after TMJ replacement, with and without lateral pterygoid muscle reattachment, were re-created in a cadaveric preparation. The laser-scanned data during the mandibular motion were used to drive 3-dimensional CT models. A movie for each mandibular motion was subsequently created for motion path analysis. Compared with mandibular motion before TMJ replacement, mandibular lateral and protrusive motions after TMJ replacement, with and without lateral pterygoid muscle reattachment, were greatly limited. The jaw motion recorded before total joint replacement was applied to the mandibular and prostheses models after total TMJ replacement. The condylar component was observed sinking into the fossa during jaw motion.

Conclusion—A motion simulator capable of re-creating and recording full range of mandibular motions in a cadaveric preparation has been developed. It can be used to simulate mandibular motions for the intact TMJ and total joint prosthesis, and to re-create and record their full range of mandibular motions. In addition, the full range of the recorded motion can be re-created as motion images in a computer. These images can be used for motion path analysis and to study the causation of limited range of motion after total joint replacement and strategies for improvement.

One major goal in temporomandibular joint (TMJ) reconstruction is restoration of normal function, which includes the physiologic range of mouth opening and the normal lateral and protrusive movements of the mandible.[1,2] The normal adult mouth opening ranges from 38 to 50 mm, the normal lateral excursions from 7 to 10 mm, and the normal protrusions from 8 to 12 mm. However, the same is not true in patients after prosthetic total joint replacement. Most patients treated with prosthetic TMJ replacement have an increase in range of mouth opening compared with their preoperative condition. It is also clear that compared with normal, their jaw motion is significantly decreased, even in the most successful alloplastic reconstructed joints using custom-made prosthesis.[1] One study showed that, before total joint replacement, the average interincisal opening was 27.5 mm (range, 4 to 50 mm) and lateral excursion was 2.1 mm (range, 0 to 5 mm).[3,4] After total joint replacement, the average interincisal opening increased to 32.6 mm (range, 4 to 56 mm) and lateral excursion was decreased to 1.7 mm (range, 0 to 5 mm). This finding is consistent with findings in other studies.[5,6]

The actual cause for the limited range of motion (ROM) after total TMJ replacement is not well understood. Several hypotheses have been postulated to explain this phenomenon. One states that the limitation in ROM is secondary to lateral pterygoid muscle (LPM) detachment.[7–9] Another states that the design of the prosthesis could limit the ROM, and another states that postoperative scar tissue formation limits ROM.[3,4,8] However, the actual cause for this limitation remains unclear.

To determine the causes of the limited ROM and improve the functional outcomes after total joint replacement, it is necessary to first develop an appropriate experimental model to simulate TMJ motions. Therefore, the purpose of this study was to develop a motion simulator capable of re-creating and recording full range of mandibular motions in a cadaveric preparation, for an intact TMJ and after total joint replacement.

Materials and Methods

The TMJ motion simulator was developed in 4 stages. The first stage was to develop the hardware for the TMJ motion simulator. It included a freestanding metal mounting frame to support a cadaveric preparation and a series of cables and pulleys to simulate the muscle forces of mandibular motion. The second stage was to re-create TMJ kinematics in a cadaveric preparation with intact TMJs. A cadaveric preparation with intact TMJs was mounted onto the hardware developed in the first stage. Its mandible was driven using the cables, pulleys, and dead weights to simulate mandibular motion. The motion was then recorded using a 3-dimensional (3D) laser scanner. The third stage was to re-create TMJ kinematics in a cadaveric preparation with unilateral TMJ replacement. A unilateral TMJ total joint replacement was performed on the same cadaveric preparation. It was then mounted onto the hardware, and mandibular motion was simulated again using the same forces that were used in the second stage. Mandibular motion was also recorded using the same 3D laser scanner. The fourth stage was to analyze the TMJ kinematics 3-dimensionally in the computer. The detailed methods are described as follows.

STAGE 1: TO DEVELOP HARDWARE FOR TMJ MOTION SIMULATOR

A surrogate (plastic) human skull was used to establish the methodology. The hardware of the TMJ simulator was supported on a freestanding metal mounting frame (Fig 1). The skull was fixed to the simulator using 3 external fixation screws that were configured as a triangle. The screws were inserted in the intracranial surface of the skull base. The skull was then oriented to the Frankfort horizontal plane by adjusting the 3 screws. In addition, a metal mounting frame was used to support the cables and pulleys used to simulate the muscle forces applied to each specimen.

Using this simulator, the realistic jaw motions can be generated through the application of the following muscle forces: the protractor muscle (LPM), the suprahyoid depressors (geniohyoid, mylohyoid, and di-gastric muscles), and the elevator muscles.[10,11] To simulate muscle contraction, 0.28-mm nylon coated cables (Berkley Steelon, Hillsboro, OH) were inserted at the center of the area of attachment of each muscle. The activation cables were secured with size 3 wire sleeves (Berkley Wire Leader Connector Sleeves, Berkley Steelon). The free ends of the cables were directed to the bottom of the frame through the pulleys. The contracting vectors of the LPM and suprahyoids and the location and the motion of the hyoid are described as follows.

LPM Contracting Vector—The LPM has 2 heads, superior and inferior.[10,12] The functions of the 2 heads are controversial.[12–18] In the present experiment, the contracting vectors of the superior and inferior heads of the LPM were averaged and combined. For each LPM, a cable was inserted in the center of the pterygoid fovea (Fig 2). The other end of

the cable was directed anteriorly and medially following the LPM vector. To allow the superior exit of the cable through the cranial base while maintaining this vector, the cable was redirected through a copper tube that had been vertically inserted from above into the infratemporal fossa. The tube was inserted through a 3- × 2-cm window that was created on the cranial base (Fig 3). The other end of the copper tube was attached to the top of the frame. The position of the tube could be adjusted in 3 dimensions to maintain the correct contracting vector of the LPM.

Suprahyoids Contracting Vectors—The mandibular depressor muscles are attached to the mandible and the hyoid bone. The anterior belly of the digastric muscle originates from a depression on the inner side of the inferior border of the mandible close to the symphysis and passes posteriorly and inferiorly where it joins its intermediate tendon. The tendon is indirectly attached to the greater horn of the hyoid by a fibrous sling. The geniohyoid originates from the genial tubercles located in the lingual aspect of the mandible on each side of the sagittal plane and runs posteriorly and slightly inferiorly to be inserted into the anterior surface of the body of the hyoid. The mylohyoid originates from the medial aspect of the body of the mandible along the whole length of the mylohyoid line in front of the last molar, and it is inserted to the corpus of the hyoid.[10,12] Based on this anatomy, the cables used to simulate these muscles were placed at the center of the areas of origin and insertion. Due to the fragile nature of the hyoid bone, it was replaced by an artificial hyoid. The 3 pairs of suprahyoids were replaced by 6 activation cables along their contracting vectors. To apply the muscle forces, the activation cables were diverted through slots on the artificial hyoid instead of attaching the cables onto the artificial hyoid (Fig 4).

Location and Motion of the Hyoid—During mouth opening, the hyoid moves backward and downward from its initial position to allow maximal mouth opening. Muto and Kanazawa[19] described the hyoid motion path during mouth opening. They indicated that hyoidale (the most anterosuperior landmark on the body of the hyoid bone) moved posteriorly and inferiorly 24.0° to the horizontal plane until the angle between nasion, sella, and hyoidale was 105.7°. Initially, we wanted to incorporate the hyoid motion path into our simulator. However, we were unable to find any study that correlated the amount of hyoid bone displacement to the interincisal distance during mouth opening. Therefore, instead of simulating the hyoid bone movement dynamically, in the present simulator, the hyoid bone was placed at its final position for maximal mouth opening.

To provide for a minimal mouth-closing force at the initial position, the elevator muscles were combined at the anterior of the mandible. A cable was attached to the lingual side of the mandibular symphysis above the mental spins (Fig 4). The cable was then directed superiorly to the top of the frame, passing through the palate and the nose to the cranial base to maintain the mouth-closing vector. It was then redirected through a pulley to the bottom of the frame and connected to a spring and a force transducer.

The free end of each cable was connected to a weight holder at the bottom of the frame. To apply the forces evenly to each pair of cables (right and left), the ends of each pair were attached to a horizontal metal rod, and the cables remained parallel to each other. The force was applied in the middle of the rod (at the bottom of the frame shown in Fig 1A). Because

of their proximity to the midline, the 2 cables for mylohyoids were connected (combined) where the force was applied. The force was applied using dead weights.

STAGE 2: TO RE-CREATE TMJ KINEMATICS IN A CADAVERIC PREPARATION WITH INTACT TMJS

In the second stage, a full range of mandibular motion was simulated on a cadaveric preparation. To record and analyze the mandibular motion, computer models of the preparation were generated. The mandibular motion was recorded using a 3D laser scanner.

A cadaver head with an intact Angle's Class I occlusion and intact craniomaxillofacial skeleton and soft tissue was used. The specimen was freshly frozen with no preservatives used to maintain soft tissue mechanics. It was stored overnight at 38°F in preparation for surgery and retest next day and sprayed liberally with 0.01M phosphate buffered saline (pH = 7.4; Sigma, St. Louis, MO) in phosphate buffered saline to keep the soft tissue moist. Room temperature was maintained at 58°F throughout preparation and testing. No overhead lights were used during the cadaver dissection.

To record the mandibular motion, 3 tracking balls were attached to the forehead and the same number to the mandible. A computed tomographic (CT) scan was performed at 0.625-mm slice thickness. The 3D CT models of the skull were generated. The mandible and their tracking balls were segmented as separate objects. They were used in the fourth stage for motion analysis in the computer, in conjunction with the recorded mandibular motions.

On the cadaveric specimen, the cranial vault above the superior temporal line was excised, leaving the temporal muscles and underlying bone intact. The brain was removed and the middle cranial fossa was exposed. The superior heads of the LPMs were exposed by creating 3- × 2-cm windows in the right and left middle cranial fossas. The windows were located laterally to the line connecting the foramen ovale and the foramen rotundum. Using a wire-passing burr, activation cables were inserted percutaneously through the preauricular skin, the neck of the condyle, and the pterygoid fovea where the lateral pterygoid was attached to the mandible. To confirm that each cable was correctly and solidly attached to the neck of the condyle, the cables were temporarily directed to exit the face through holes created through the anterior and posterior walls of the maxillary sinuses. Both cables were activated and a mandibular protrusive motion was observed. The correct installation of the cables was also confirmed by fluoroscopy. Once the installation of LPM cables was confirmed, metal conduits (ie, copper tubes) were inserted from above, through the middle crania fossa windows, and were fixed where pterygoid plates were located, the same as indicated in Figure 2. The cables were then redirected through this conduit, mimicking the pterygoid plate end of LPM attachment. This ensured the activation vector of the cable was the same as the LPM contracting vector. The insertion end of the conduits was cut at 45° to ensure that the cable precisely maintained the correct LPM contracting vector during its activation process. The cables were redirected by a pulley to the bottom of the frame for application of forces.

The hyoid was exposed, and the suprahyoid muscles were identified and dissected from the mandible. The cables representing the suprahyoids were inserted and secured to the

mandible where the muscles anatomically attach (center of the area of attachment; Fig 5). The neck was excised, leaving the masticatory muscles intact. A closing cable was inserted in the same manner as on the surrogate skull.

The cadaveric head was mounted onto the TMJ simulator with the 3 external screws, the same as indicated in Figure 3. The Frankfort plane of the head was orientated to the horizontal level. The artificial hyoid was installed and adjusted in the same manner as in the surrogate skull. This was done by first establishing the position of the hyoid at the closed mouth position based on the measurement of the real hyoid position from the 3D CT scan and then calculating the position of the artificial hyoid at its maximal mouth opening as described by Muto and Kanazawa.[19] The angle between nasion, sella, and hyoidale of 106° was confirmed using fluoroscopy. Figure 6 shows the prepared cadaveric head mounted on the TMJ simulator and positioned in a fluoroscopic radiographic machine ready for the experiment.

Once the head was mounted on the simulator, the muscle forces were applied to the activation cables representing the LPM and mylohyoid, digastric, and geniohyoid muscles. Maximum muscle forces were obtained from a published and validated model (Table 1).[20–22] These maximum muscle forces served as the boundary values used to prevent the application of unrealistic muscle forces. A mouth-closing force was initially applied to maintain the centric occlusion. To open the mouth gradually in a normal mouth-opening pattern, the force applied to each cable was gradually adjusted until the maximum mouth opening was reached. For the lateral motion, only 1 of the LPM cables was activated at a time. For the protrusive motion, both LPM cables were activated simultaneously (Table 2).

The mandibular opening motion was recorded in 8 intervals, whereas the right, left, and protrusive motions were recorded in a single interval (Table 2). To record mandibular motion, the tracking balls attached to the forehead and the mandible were 3-dimension ally scanned at each interval using a high-resolution laser scanner (MicroScribe-Solution Technologies Inc, Oella, MD; Fig 7). To ensure the condyle-fossa relation was within the normal physiologic condition, each interval was also recorded using fluoroscopy.

STAGE 3: TO RE-CREATE TMJ KINEMATICS IN A CADAVERIC PREPARATION WITH UNILATERAL TMJ REPLACEMENT

The right TMJ of the same cadaver head was replaced with a total TMJ prosthesis (Biomet Microfixation Inc, Jacksonville, FL; Fig 8). According to the clinical protocol of total TMJ replacement,[6,23,24] the condyle was first resected, and the lateral aspect of the ramus and the mandibular fossa was recontoured with preauricular and submandibular incisions. The appropriate TMJ fossa and condyle components were then placed and secured in intermaxillary fixation. In addition, the LPM cable was reattached to the hole on the prosthetic condylar neck that was predrilled by the manufacturer to simulate the pterygoid fovea. This was done to allow the simulation of possible LPM reattachment. After the wound was closed layer by layer, a CT scan was performed at 0.625-mm slice thickness. The 3D CT models of the skull were generated. The mandible, condylar prosthesis, and tracking balls were segmented as separate objects. Because of artifacts, the CT image of the implanted prosthesis was less than detailed. Therefore, this image was replaced with the

more accurate computer-aided designing model of the prosthesis that was directly obtained from the manufacturer. To replace the condylar component, the computer-aided designing model of the condylar prosthesis was registered to the CT prosthesis model using a surface best-fit matching method.[25] The fossa component was incorporated by registering the screws on the CT scan to the screw holes on fossa component. This was necessary because the fossa was made by polyethylene and not shown in CT scans. Two different colors were then assigned to the fossa and condylar components.

The TMJ kinematics after total joint replacement was re-created in 2 different fashions: *1*) activating the right LPM cable to the prosthetic condyle to simulate the reattachment of the LPM and *2*) not activating the right LPM cable to simulate conventional TMJ alloplastic reconstructive surgery. For each condition, the same muscle forces used in stage 2 (for intact mandible) were used to generate 8 intervals of the mouth opening and a single interval of the right, left, and protrusive motions. The motions were recorded in the same manner used in stage 2.

STAGE 4: TO ANALYZE TMJ KINEMATICS 3-DIMENSIONALLY

The mandibular motions, recorded before and after total joint replacement, were used to re-create the TMJ kinematics in the computer (Fig 9). They were used to “drive” 3D computer mandibular models. The recorded motion was a sequence of the positions of the mandibular tracking balls in relation to the reference forehead tracking balls. Using computer animation software (3D Studio Max; Autodesk Inc, San Rafael, CA), the mandibular model was linked to the mandibular tracking balls. Afterward, the laser-scanned forehead tracking balls within the entire motion sequence were registered to the 3D CT forehead tracking balls. The CT mandibular tracking balls were then registered to each interval of laser-scanned mandibular balls, resulting in a sequence of motion for the computer model of the mandible. The condyle-fossa relation at each interval was compared with the fluoroscopic image that was captured at the same interval to ensure the condylar motion was within the normal physiological condition. For each sequence a movie (in audio video interleave [avi] format) of mandibular motion was created. These movies were used to study the jaw motion pattern before and after total joint replacement, with and without the LPM reattachment.

A set of landmarks, ie, maxillary and mandibular dental midlines, and the centers of the right and left condyle, were digitized onto the CT models. Motion analysis was completed by tracking the position and orientation of each landmark. Because the movie frames between intervals were interpolated automatically (8 intervals for opening, 2 for lateral motions, and 1 for protrusive motions), only the motion at each interval was analyzed. Whether mandibular motion could follow a normal pattern after unilateral total joint replacement was tested. Mandibular motion recorded before total joint replacement was applied to the mandibular model after total joint replacement to evaluate whether the prosthetic condyle-fossa relation was within the normal physiologic condition.

Results

A TMJ motion simulator was successfully developed. It was capable of creating and recording a full range of mandibular motions in a cadaveric preparation. To analyze the TMJ

kinematics, the recorded mandibular motion was subsequently used to drive 3D computer models. At each interval of mandibular motion, the condyle-fossa relation was examined and found identical to the fluoroscopic image recorded at the same interval.

After unilateral total joint replacement, the mandibular opening motion was comparable to the preoperative mandibular motion. However, the mandibular lateral and protrusive motions, with and without LPM reattachment, were greatly limited (Figs 10 to 13; click the images in Fig 13 to see the movies, available in the online version of the article). Finally, after applying the mandibular motion recorded before the total joint replacement to the mandibular and prosthetic models after the total TMJ replacement, the condylar component was observed sinking into the fossa during jaw motion (Fig 14; click the images to see the movies).

Discussion

Traditionally, TMJ kinematics has been studied using mathematical or finite element models.[8,26] These mathematical computer models were useful in analyzing the contributions of the masticatory muscles to opening and closing movements. These could have contributed significantly to the design of TMJ prosthesis. Unfortunately, these types of studies were not considered when the current TMJ prostheses were designed (personal communication with engineers at TMJ prosthesis companies). In addition, most TMJ devices have been only bench-tested over time at mathematical postulated loads. The actual loads have not yet been determined under normal or compromised states.[8,27] Therefore, there is an urgent need to understand the TMJ kinematics to solve the TMJ motion limitation after alloplastic joint replacement.

Using an appropriate experimental model to study TMJ kinematics after total joint replacement is critical. There are only a few studies that have used dry skulls to simulate mastication.[28,29] Hatcher et al[28] developed an in vitro mechanical simulator using a human dry skull to measure the TMJ loads during mastication. In this simulator, muscle forces were simulated by wires and the disc was simulated by synthetic material. However, the LPM, which has a major effect on mouth opening and clenching, was not included in the simulator. Meyer et al[29] simulated the external masticatory forces in a static simulator. The simulator consisted of a dry human mandible, an artificial fossa covered with a silicon membrane, and a set of wires to simulate the masticatory muscles. Although their simulator was capable of reproducing a wide range of masticatory movements, the TMJ surrounding soft tissues, ie, capsule and ligaments, were not included in the simulator, thus making the results less than realistic to a physiologic situation. Nonetheless, there was no report on using fresh cadaveric head to study TMJ kinematics.

To create mandibular motion and to study TMJ kinematics, it is necessary to consider active forces and passive resistance. Active forces are generated by muscle contraction, whereas passive resistance contributes to jaw motion.[30] The passive resistance usually originates from the passive muscles, connective tissues, ligaments, and skeletal constraints, such as the TMJ bony structures and the contacts of the teeth. During mandibular movement, a balance occurs between the active and passive forces.[31] This balance determines the border

motions.[30] Although the active forces have been simulated in cadaveric and mathematical models in previous studies,[28,29] passive resistance has been simulated only in mathematical models.[30–33] To generate a realistic mandibular motion, it is the authors' opinion that the simulation must be completed using active forces and passive resistance.

The present simulator integrated the active forces, passive resistance, and gravity during mandibular motion. The active forces were deployed to the mandible by activation cables. The vector of each cable was adjusted to the same contraction vector of each muscle. The passive resistance in this simulator was from the original masticatory muscles, ligaments, and TMJs with an intact soft tissue envelope. Gravity was overcome by an additional closing cable on the mandible. This simulator allowed the recording of mandibular motion and transferring it to 3D CT models, and thus regenerating the 3D motions on the CT mandible. This was crucial for studying 3D motion path.

There are several drawbacks to the present cadaveric simulator. Like other cadaveric studies, magnetic resonance imaging and computed tomography are necessary to examine the cadaveric head before the experiment. This is to confirm that the cadaveric head has a normal TMJ. The second drawback is that the closing forces were summarized at the mandibular symphysis rather than at the coronoid process.[11] The third drawback is that, although the cadaver was fresh, the passive resistance may not be the same as in a live human being. The cadaver underwent several lengthy procedures during which tissues properties may have changed. The activation cable was inserted into the mandible as a point, rather than an area like the muscle attachment. This may have resulted in an improper force distribution on the mandible.

The purpose of this project was to create a methodology for re-creating TMJ kinematics in a cadaveric model and analyzing them in the computer. Therefore, the motion analysis should not be used to make any definitive conclusions. However, the preliminary results indicated that the mandibular lateral and protrusive motions were greatly limited after total joint replacement. With the LPM reattachment, the lateral and protrusive motions could be improved. Nonetheless, with the current design of the TMJ prosthesis, it was still impossible to achieve a normal jaw motion, even with the LPM reattached. This may have been due to the design of the prosthesis. After total joint replacement, the computer simulation clearly showed that the condylar component sank into the fossa component when the recorded preoperative mandibular motion was applied to the mandible. In addition, the test was performed on only 1 cadaver. In this particular specimen, the TMJ prosthesis did not limit maximal mouth opening, although it impaired translational and protrusive movements. The results will likely vary for each cadaver and each different TMJ prosthesis installation. The movements may be impaired in some specimens, whereas others may not be impaired.

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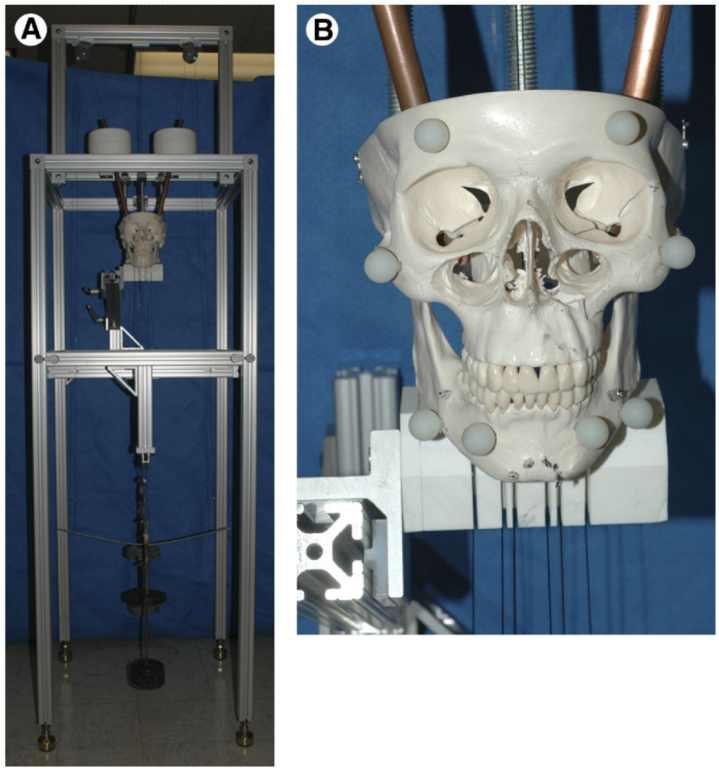

FIGURE 1.

Temporomandibular joint motion simulator. *A*, Hardware for temporomandibular joint motion simulator. *B*, Mounted surrogate skull with an artificial hyoid bone.

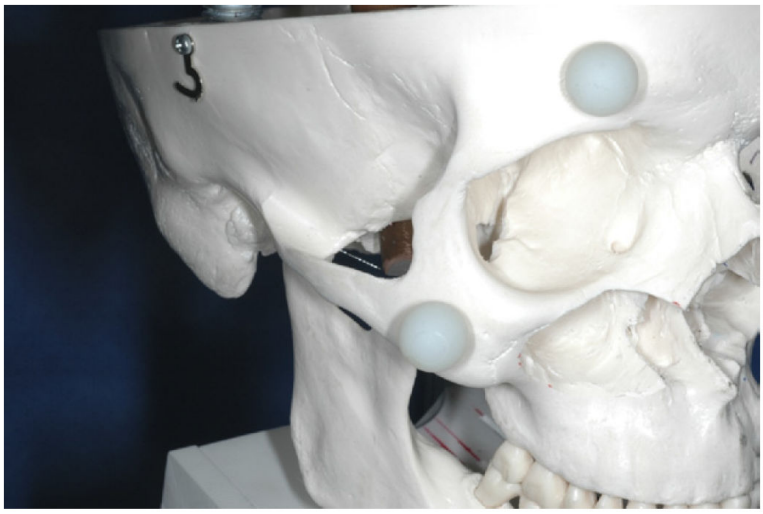

FIGURE 2.
Lateral pterygoid muscle vector was redirected out of the skull.

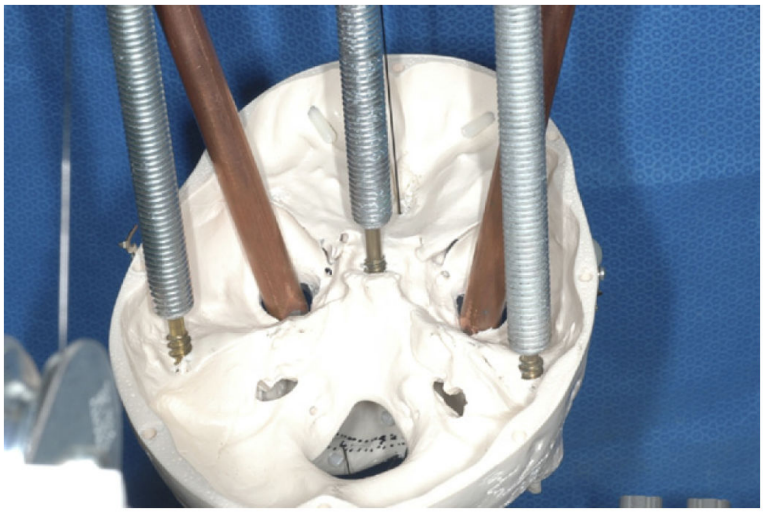

FIGURE 3.
Vertexes of lateral pterygoid muscles were redirected out of the skull through copper pipes placed on the cranial base above infratemporal fossa. The 3 threaded bars were used to mount the skull onto the simulator.

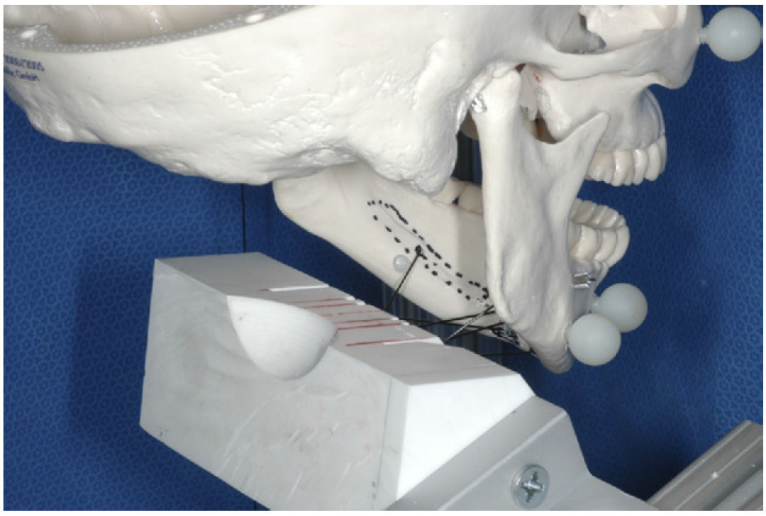

FIGURE 4.
Vectors of suprahyoid muscles were directed to an artificial hyoid bone.

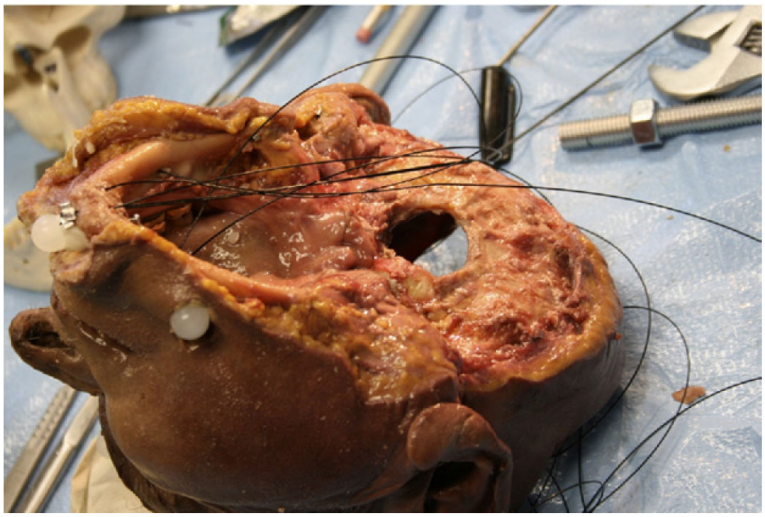

FIGURE 5.
Cables were attached to anatomic locations of the suprahyoid muscles.

FIGURE 6.
The cadaveric head was prepared and mounted on the temporomandibular joint simulator. The simulator was placed on a fluoroscopic radiographic machine.

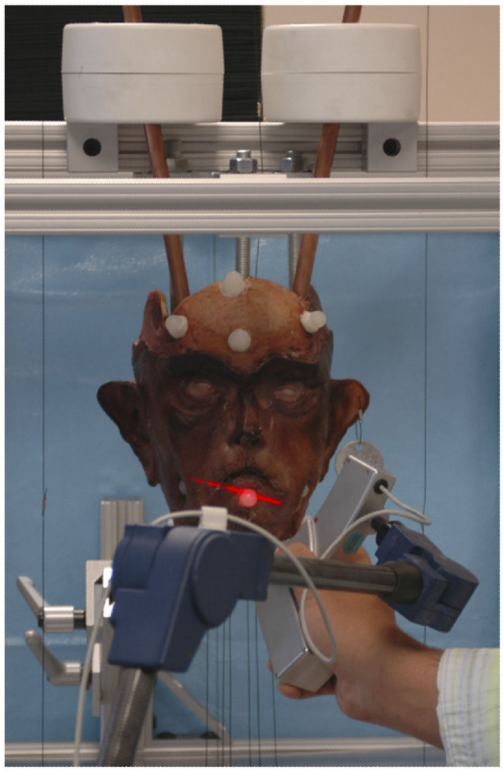

FIGURE 7.
A handheld high-resolution laser scanner was used to scan the fiducial tracking balls at each interval. The mouth in this figure was in the closed position.

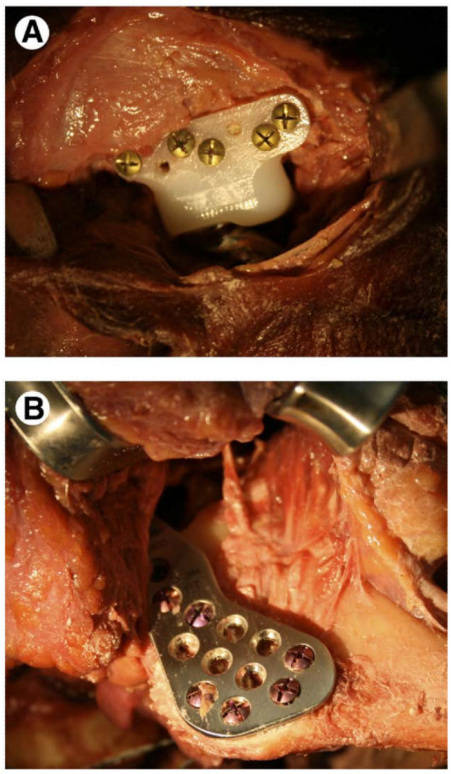

FIGURE 8.
The right temporomandibular joint of the same cadaver head was replaced with a total temporomandibular joint prosthesis. *A*, Fossa component. *B*, Condyle component.

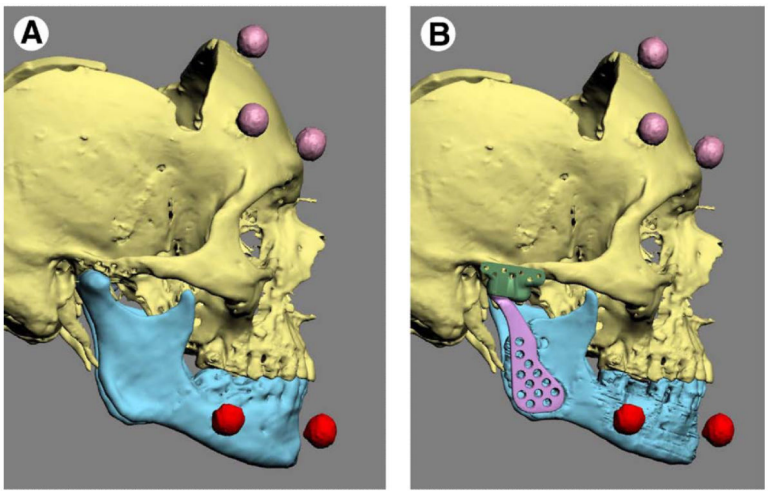

FIGURE 9.

Three-dimensional computer models for studying mandibular motion (*A*) before and (*B*) after total temporomandibular joint replacement.

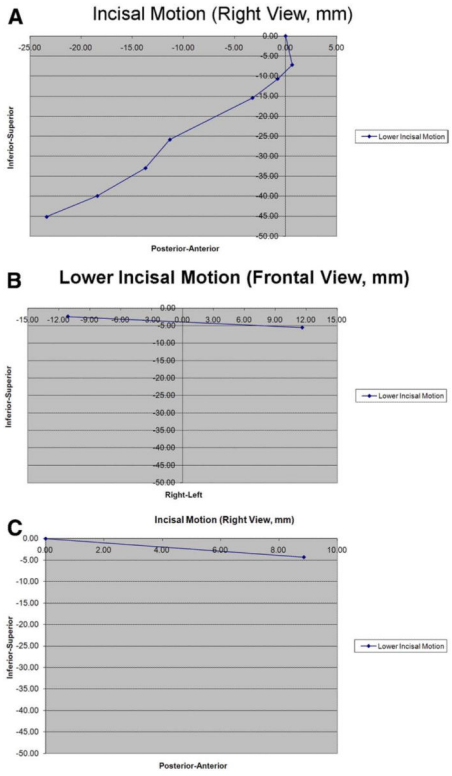

FIGURE 10.

Mandibular motion in millimeters (mm) at lower incisor tip before total temporomandibular joint replacement. *A*, Opening movement (right view). *B*, Lateral movement (frontal view). *C*, Protrusive movement (right view).

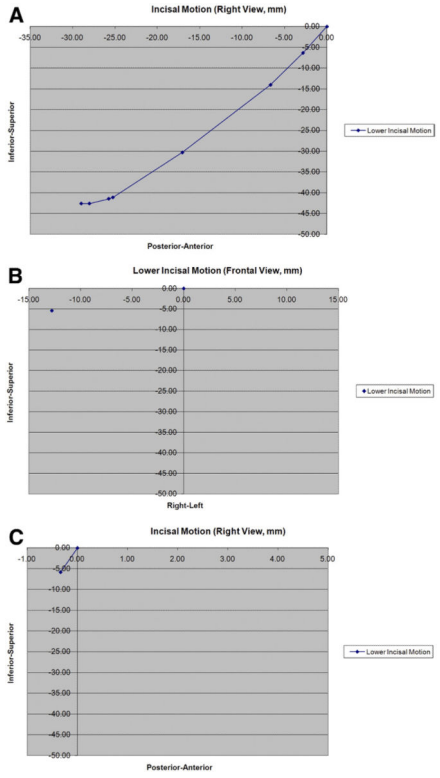

FIGURE 11.

Mandibular motion in millimeters (mm) after right total temporomandibular joint replacement without lateral pterygoid muscle reattachment. *A*, Opening movement (right view). *B*, Lateral movement (frontal view). *C*, Protrusive movement (right view).

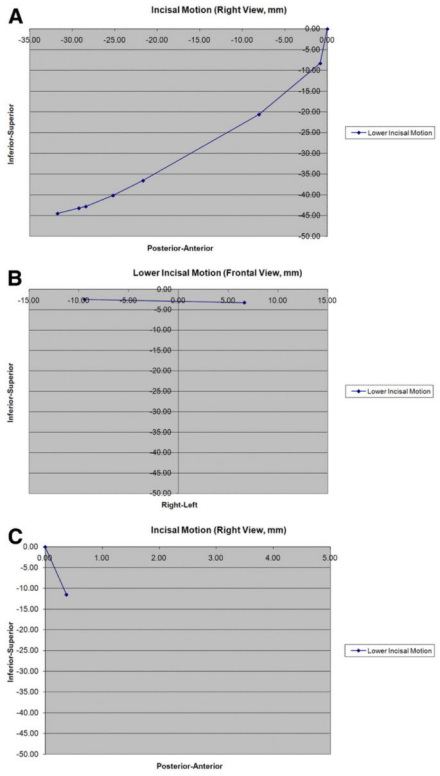

FIGURE 12.

Mandibular motion in millimeters (mm) after right total temporomandibular joint replacement with lateral pterygoid muscle reattachment. *A*, Opening movement (right view). *B*, Lateral movement (frontal view). *C*, Protrusive movement (right view).

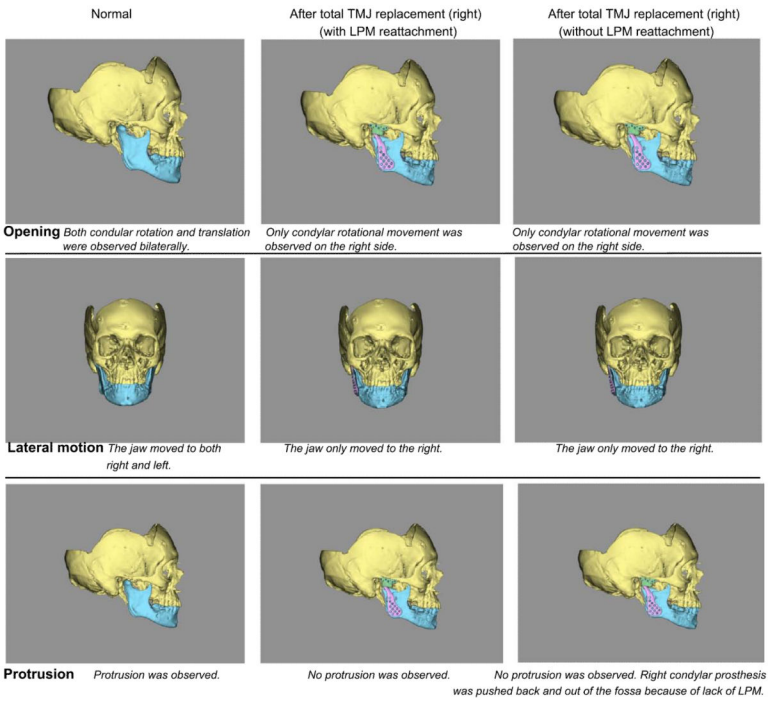

FIGURE 13.

Movies of re-created jaw motions of computer models (click each image to activate the movies, available in the online version of the article).

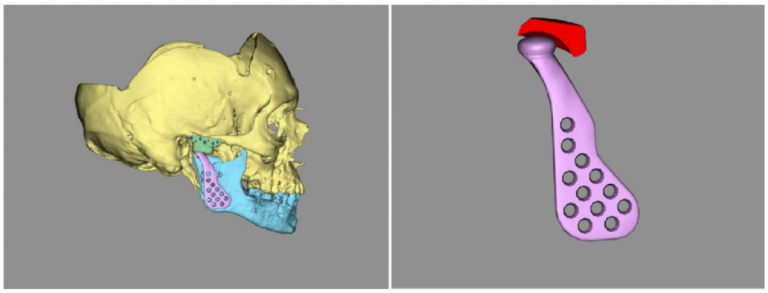

FIGURE 14.

Motion recorded before total joint replacement was applied to the mandibular and prosthesis model after total joint replacement. The *right figure* showed the same motion on an enlarged view with only the top inner half of the fossa and condyle. The condyle sank (penetrated) into the fossa during the jaw motion following the normal path (click each image to activate the movies, available in the online version of the article).

Table 1

MAXIMUM MUSCLE FORCES

Muscles	Force (N)
Lateral pterygoid	150.8
Digastric and geniohyoid	85.2
Anterior mylohyoid	63.6

Table 2

MUSCLE FORCES APPLIED TO THE HEAD TO SIMULATE JAW MOTION

Motion Type	Interval	LPM (N)	Geniohyoid and Digastric (N)	Mylohyoid (N)
Opening	1	8.00	1.00	1.00
	2	79.20	18.80	9.90
	3	83.64	23.25	9.90
	4	92.54	32.15	14.35
	5	101.44	36.60	18.80
	6	101.44	41.05	14.35
	7	110.34	41.05	14.35
	8	119.24	49.95	23.25
Right	1	74.75	5.45	1.00
Left	2	74.75	5.45	1.00
Protrusion	1	150.39	14.35	1.00

Abbreviation: LPM, lateral pterygoid muscle.