A COMPARISON OF SIMULATED JAW DYNAMICS IN MODELS OF SEGMENTAL MANDIBULAR RESECTION VERSUS RESECTION WITH ALLOPLASTIC RECONSTRUCTION

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Statement of problem. Composite mandibular resection resulting in mandibular discontinuity can alter jaw motion, occlusal forces, and mastication, whether or not the jaw is reconstructed. The biomechanical events associated with these changes are difficult to assess clinically and, therefore, are not well documented or researched.

Purpose. The purpose of this study was to model movements of a mandible with a discontinuity defect, and to compare them to movements of a mandible with its continuity restored by alloplastic reconstruction.

Material and methods. Computational models were created with a novel simulation platform. The variables designed into the models included gravity, external forces, and jaw muscle activity. Each jaw was observed at rest, when opened by external force or by muscle drive, and during the generation of unilateral occlusal force on the nonoperated side. Scarring was simulated with springlike forces. Outputs included individual muscle forces and torques, as well as mandibular incisor and condylar motions.

Results. Both models displayed plausible resting postures, and jaw opening with deviation toward the defect side when scarring was simulated. Opening caused by downward force on the incisors differed from that due to muscle activation. Jaw rotations during unilateral molar contact on the unaffected side were muscle specific and influenced by mandibular discontinuity.

Conclusions. Plausible jaw movements after hemimandibulectomy and/or alloplastic reconstruction could be predicted by dynamic modeling. The effect of soft tissue forces on jaw posture and movements varied with the condylar support available. In both models, different opening trajectories were produced by external force on the jaw and by jaw muscle activation. Mandibular rotation during unilateral molar contact depended on which muscles were activated, and the availability of bilateral condylar support. (J Prosthet Dent 2010;104:191-198)

CLINICAL IMPLICATIONS

Computational models designed with bioengineering software can simulate musculoskeletal mechanics in compromised mandibles, provided adequate clinical data are available for their validation. Functional records from postsurgical patients are needed to advance the technology beyond its current value as a hypothetical construct.

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Vascularized osteocutaneous, osteomyocutaneous, and alloplastic grafts are often used to restore mandibular continuity after hemimandibulectomy,[1-5] but not all graft reconstructions necessarily require reconstruction of the temporomandibular articulation. While grafting can provide a functional joint,[6,7] complications can include erosion of the temporal fossa, dental malocclusion, infection, and graft migration.[6,8,9] With or without articular reconstruction, hemimandibulectomy is often followed by deficiencies in mastication, speech, and other orofacial functions.[2,10-12] Typically, the mandible deviates to the resected side on opening, and mastication is performed on the unaffected side,[13,14] often requiring the aid of a guide flange prosthesis for the dentate patient, or a widened occlusal table in the maxillary prosthesis for the edentulous patient. Altered sensation, reduced salivary flow, limited or compromised tongue function, and changes in the biomechanics of the masticatory system can all affect the manipulation and comminution of food,[11,14-16] and remain major concerns in oral rehabilitation.

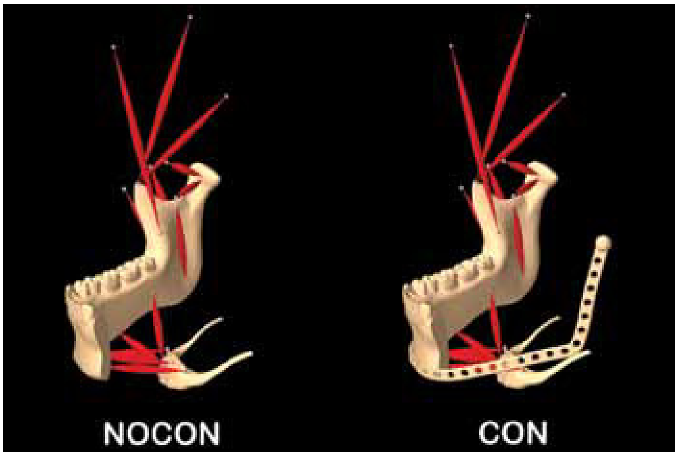
Functional parameters are often recorded for the intact masticatory system,[17] but are rarely obtained after hemimandibulectomy. Although jaw opening may not be unduly restricted, anecdotal information and clinical observations suggest that the mandible often deviates to the affected side on opening. In addition, mastication on the unaffected side can be accompanied by rotation of the mandibular arch away from the maxillary occlusal plane, which does not occur during normal function.[17] These effects are most evident in the anterior sextant. Contributing factors include asymmetry in the remaining musculature, the unilateral articulation in mandibles without continuity, postoperative tissue scarring, as well as ongoing and progressive fibrosis following radiation therapy.

Computational models have successfully reproduced jaw dynamics in the intact masticatory system[18-24] and, therefore, seem appropriate for analyzing the biomechanics of the compromised mandible. Such models would be expected to display jaw resting postures and movements typical of those observed clinically. The purpose of the present investigation was to compare the dynamic behavior of 2 posthemimandibulectomy computational models, one simulating a mandible with discontinuity, and the other its reconstruction with an alloplastic graft to create a functional temporomandibular articulation. In both situations, mandibular postures and movements were modeled with the jaw at rest, during opening movements caused by external force and muscle activation, and on jaw closing with occlusal contact on the unaffected side. The overall goals of the study are to demonstrate the potential value of computational modeling in understanding the biomechanics of tissue loss, and to suggest parameters which could be measured clinically to validate future model predictions.

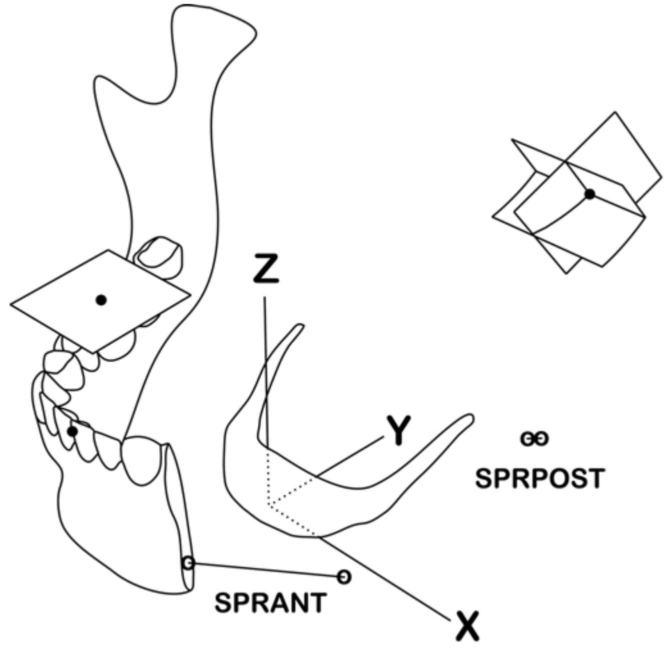
MATERIAL AND METHODS

The computational models are illustrated in Figure 1. Model NOCON (no condyle) simulated a left-side, composite jaw resection from the condyle to the left canine, without restoration of mandibular continuity. Model CON (graft-related condyle) simulated a left-side resection with continuity restored by means of an alloplastic graft similar to that described by Marx et al.[16] Both models were created with a novel software platform (ArtiSynth; Electrical and Computer Engineering and Computer Science Departments, The University of British Columbia, Vancouver, Canada).[25-26] Aside from a fixed hyoid apparatus, the excised components, and the simulated graft, these models were otherwise identical to a generic dynamic model of the intact masticatory system described elsewhere.[19] In both models, the right anterior, middle, and posterior temporalis (RAT, RMT, RPT), right deep and right superficial masseter (RDM, RSM), right medial pterygoid (RMP), right superior and inferior lateral pterygoid (RSP, RIP), right mylohyoid (RMY), right and left geniohyoid (RGH, LGH), and right and left digastric (RDI, LDI) muscles were simulated with actuators. These had active and passive muscle properties, and were driven by user-defined functions.[23,26,27]

When the jaw was in the maximal intercuspal position, the right condyles in both models and the alloplastic condyle in CON were centered in their articular fossae. Each was constrained by frictionless contact of its anatomical center point against a curvilinear surface offset from and similar in shape to the articular fossa



1 Study models. Model NOCON shows jaw resection without mandibular continuity. Model CON shows continuity restored by alloplastic grafting. Both models have left-side muscle loss.



2 Model conventions and restraints. Model illustrated is NOCON with SPRANT soft tissue spring. In CON, SPRPOST spring was attached to graft's gonial angle (not shown). For clarity, only left-side articular constraining surfaces are illustrated. Black spheres indicate incisor point, left condylar center, and molar contact point locations in maximal intercuspal position. Positive x, y, and z axes originate in hyoid.

and eminence, and also by 2 additional planar walls.[19] The medial planar wall was oriented 15 degrees to the parasagittal plane, and the posterior wall was perpendicular to the superior guiding surface (Fig. 2). The temporomandibular ligaments were not simulated, so each condyle could translate laterally. A flat occlusal plane prevented upward movement of the distobuccal cusp of the right mandibular first molar, simulating contact between 0-degree flat-cusped tooth anatomy.

Passive soft tissue forces representing tissue scarring were modeled with linear, damped springs. These had stiffnesses of 200 N/m and viscous damping coefficients of 10 N•s/m to restrict jaw motion without eliminating it. When enabled, the springs permitted incisal separations of at least 15 mm, and counteracted the tendency of the jaw to position itself to the right as a result of passive muscle forces on that side. In NOCON, an anterior spring attached to the sectioned face (SPRANT) drew this end of the native mandible laterally, posteriorly, and inferiorly from its initial position. In CON, a posterior spring attached to the gonial region of the graft (SPRPOST) initially drew the gonial angle of the graft inferiorly and posteriorly, and thereafter created tensile forces proportional to gonial displacement in any direction (Fig. 2).

The conventions expressing spatial coordinates are shown in Figure 2. The x-y plane was oriented to the Frankfort horizontal plane. Each origin was in the body of the hyoid, with positive x-,y-, and z-axes indicating left lateral, posterior, and superior, respectively.

Movements were simulated using Symplectic Euler integration and maximum step sizes of 0.0001 seconds. The relaxed rest position of the mandible without postural muscle activity[28] (RRP) was assessed with and without soft tissue restraint 1 second after gravitational acceleration from the maximal intercuspal position. External force applied downwards to the mandibular incisors perpendicular to the occlusal plane (FORCE) simulated manual jaw opening from RRP with soft tissue restraint. This force increased at 10 N/s, and the simulation was terminated when the incisor point reached approximately 30 mm of inferior displacement. Jaw opening due to muscle activation (OPEN) simulated voluntary jaw opening from RRP with soft tissue restraint. Here, RSP, RIP, RDI, and LDI were driven simultaneously, reaching 10% of maximum contraction in 0.5 seconds. Unilateral molar contact on the unaffected side on jaw closure from RRP (UNIMOL) was simulated by activating individual jaw closing muscles in the presence of soft tissue restraint. RAT, RMT, RPT, RDM, RSM, and RMP were each driven independently to 10% of maximum contraction in 0.5 seconds, similar to the protocol used by Koolstra and van Eijden.[29]

Locations and displacements of a midline mandibular incisor point and condylar centers were predicted in each model, as well as muscle forces and torques expressed at the center of mass. Data were stored as text files for postprocessing, and animated versions of the models were recorded in digital video format.

RESULTS

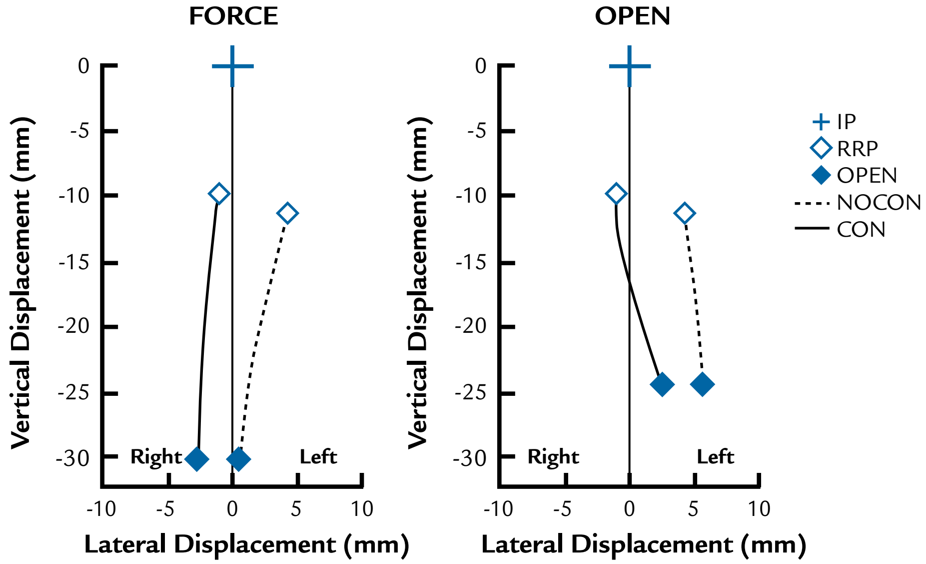
Relaxed resting jaw posture

Table I describes displacements of the incisor point and condyles at RRP for both models, with and without soft tissue constraints. Without these constraints, each jaw rotated around its right condyle, the incisor point moving laterally to the right and inferiorly, with little displacement of the right condyle. In CON, the left (grafted) condyle moved 7-8 mm anteriorly and inferiorly. Addition of soft tissue constraints altered both RRPs. In NOCON, SPRANT caused the jaw to rotate to the defect side, the incisor point displacing markedly left, posteriorly and inferiorly, and there was minimal displacement of the right condyle. In CON, the effect with SPRPOST was less, the jaw remaining

TABLE I. Incisor point and condylar center displacements at relaxed rest position (RRP)

Spring	Incisor Point (mm)			Right Condylar Center (mm)			Left Condylar Center (mm)		
	x	y	z	x	y	z	x	y	z
NOCON									
None	−7.77	−0.34	−12.05	0.47	−1.46	−0.96	–	–	–
SPRANT	4.12	8.77	−11.25	0.14	−0.44	−0.30	–	–	–
CON									
None	−6.76	0.23	−12.46	0.52	−1.63	−1.06	0.16	−7.58	−7.31
SPRPOST	−0.91	3.38	−9.77	0.16	−0.94	−0.63	0.15	−1.65	−1.85

Displacements are measured from initial locations in maximal intercuspal position. SPRANT and SPRPOST are springs representing soft tissue forces (see text). Negative signs for axes x, y, and z indicate right lateral, anterior, and inferior, respectively.



3 Frontal plane displacements of mandibular incisor points during FORCE and OPEN. In models NOCON and CON, movements began from jaw's relaxed rest position (RRP). Trajectories referenced to maximal intercuspal position (IP) (large crosses).

closer to the midline at a reduced incisal separation.

Force-induced jaw opening

Trajectories of incisor point displacement during FORCE are compared in Figure 3. In both models, inferior displacement of the incisor point closely approximated the opening target of 30 mm with forces less than 5 N (3.29 N and 3.38 N for NOCON and CON, respectively). In NOCON, the incisor point approached the midline as the jaw opened, ending 8.38 mm posterior to its maximal intercuspal position (not shown). The path in CON paralleled that in NOCON, but began and ended on the right (unaffected) side, indicating frontal clockwise jaw rotation.

Muscle-guided jaw opening

Trajectories of incisor point displacement during OPEN are compared in Figure 3. In both models, the incisor point moved to the left (affected) side. In NOCON, the marked lateral movement of the incisor point to the operated side partly resulted from its initial position in RRP, where it was already displaced to the left. Greater lateral deviation occurred in CON, where the incisor point moved initially to the right, then markedly to the left.

Muscle-guided jaw closing

Displacements of the incisor points and condyles for UNIMOL in both models are reported in Tables II and III, and graphic examples of jaw rotation in NOCON are illustrated in Figure 4.

In NOCON, the actions of RAT, RMT, RPT, and RDM were generally homologous. The most common effect was movement of the incisor point laterally to the left and posteriorly, especially for RPT and RDM. This was associated with marked lateral displacement of the right condyle. RPT caused significant superior movement of the incisor point, and excessive movement of the right condyle posteriorly and inferiorly along its posterior planar constraint. These marked translations and rotations are shown collectively in Figure 4. RSM activation caused excessive lateral movement of the incisor point to the left (deficient) side, as well as posteriorly and inferiorly. Here, there was minimal displacement of the right condyle, indicating predominant 3-dimensional jaw rotation. RMP activation moved the incisor point excessively left, posteriorly and superiorly. Although there was no displacement of the condyle, RMP had a strong rotational action on the jaw, different from that due to RSM activation (Fig. 3).

The effects of muscle activation in CON, with one exception, were not as striking. Contraction of RAT alone caused a small right lateral, anterior, and inferior incisor point movement, with minimal displacement of the right condyle, accompanied by a small right lateral, anterior, and infe-

Table II. Incisor point and condylar center displacements in model NOCON with individual closing muscle activation in right molar contact (UNIMOL)

NOCON

Muscle	Incisor Point (mm)			Right Condylar Point (mm)			Left Condylar Point (mm)		
	x	y	z	x	y	z	x	y	z
RAT	0.89	10.45	1.29	−13.12	0.00	0.00	–	–	–
RMT	4.84	14.15	0.39	−12.36	0.00	0.00	–	–	–
RPT	7.61	16.67	4.23	−11.70	5.19	−6.19	–	–	–
RDM	7.90	13.29	−0.56	−7.94	0.00	0.00	–	–	–
RSM	20.13	19.40	−4.43	0.20	−0.63	−0.43	–	–	–
RMP	10.64	6.91	2.27	0.00	0.00	0.00	–	–	–

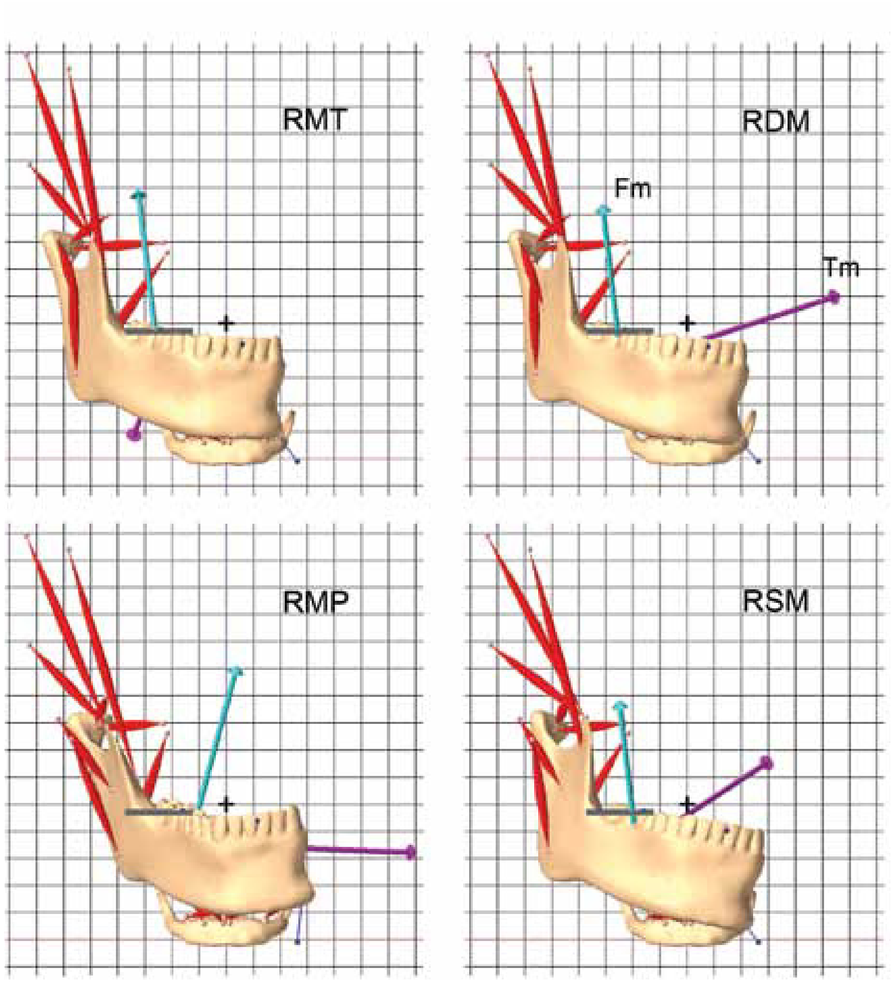
Displacements are measured from initial locations in maximal intercuspal position. Negative signs for axes x, y, and z indicate right lateral, anterior, and inferior, respectively. Muscle abbreviations are described in text.

Table III. Incisor point and condylar displacements in model CON with individual closing muscle activation in right molar contact (UNIMOL)

CON

Muscle	Incisor Point (mm)			Right Condylar Point (mm)			Left Condylar Point (mm)		
	x	y	z	x	y	z	x	y	z
RAT	−1.76	−0.60	−0.40	−0.52	0.00	0.00	−0.58	−0.07	−3.25
RMT	−0.48	0.07	−0.44	−0.27	0.00	0.00	−0.36	1.57	−3.94
RPT	0.11	2.29	0.12	0.00	4.71	−5.61	0.00	4.97	−5.92
RDM	−0.67	1.07	−2.63	−0.31	0.00	0.00	−0.48	2.20	−5.38
RSM	3.91	0.40	−1.19	0.59	−1.85	−1.20	−0.91	8.48	−15.37
RMP	1.88	−1.11	0.41	0.46	−1.42	−0.94	0.44	0.00	0.00

Displacements are measured from initial locations in maximal intercuspal position. Negative signs for axes x, y, and z indicate right lateral, anterior, and inferior, respectively. Muscle abbreviations are described in text.



4 NOCON jaw postures caused by individual closing muscle activation in right molar contact. Simulations halted when jaw motion became unrealistic at 1.36, 1.45, 1.43, and 1.19 seconds for RMT, RDM, RMP, and RSM, respectively (muscle abbreviations described in text). Muscle forces (Fm) and torques (Tm) expressed at jaw centers of mass indicate directions only (scaled for clarity). Incisor point locations in maximal intercuspal position indicated by crosses. Grid spacing is 10 mm.

rior displacement of the left condyle. Activation of RPT caused a predominant posterior and superior movement of the incisor point, with excessive displacement of both condyles posteriorly and inferiorly. RSM activation caused movement of the incisor point to the defect side, with minimal displacement of the right condyle, plus an unlikely posterior and inferior displacement of the left condyle.

DISCUSSION

Dynamic modeling can be used to study jaw biomechanics by simulating the effects of mandibular surgery and reconstruction. The approach is physics based, and suitable for investigating complex dynamic interactions amongst multiple components. Anatomical structures can be readily modified, and tissue properties can be assigned provided their parameters are known.

Predictably, the RRPs occurred at a wider incisal separation than clinical postural rest because low-grade postural muscle activity was not simulated.[28] Without soft tissue influences of any kind, both models produced unlikely resting postures well to the right of the midline. These might be expected since the jaw's gravitational acceleration was solely resisted by passive forces from the right-sided muscles. Soft tissue forces on the defect (operated) side, especially those due to scarring, would normally have a restraining effect on this motion, so the RRPs obtained with SPRANT and SPRPOST seem in line with clinical impressions. Also, less incisal separation would be anticipated clinically due to postural muscle activity. Jaw deviation in RRP was less for CON than for NOCON, suggesting that scarring in a jaw with a bilateral articulation could result in a relatively normal RRP.

The mandible's clockwise rotation in the frontal plane in RRP in both models suggested that elevation from this position would tend to engage the right molars before the left, assuming there are teeth on the defect (operated) side. A more superiorly directed "scar" in NOCON oriented towards the parapharyngeal region would tend to elevate the mandible more on the defect side if there was no condyle to resist jaw motion. The same is true if soft tissue forces exceeded passive muscle forces during opening, restricting inferior movement of the deficit side more than the unaffected one. Either scenario would result in counterclockwise jaw rotation in RRP, causing first tooth contact on the side of the defect. Out of curiosity, this possibility was tested in NOCON with a superiorly directed, more proximally located spring, which reduced incisal separation and caused counterclockwise jaw rotation.

The motions caused by FORCE reflected the different components in the 2 models. Both easily reached their opening targets of 30 mm with low applied forces of 3-4 N. In NOCON, SPRANT functioned as a simple tether, freely allowing incisal separation. In CON, however, SPRPOST acted closer to the jaw's transverse axis of rotation and limited movement in any direction. High stiffness values assigned here would be expected to restrict jaw motion, and it is significant that the stiffness of wounded porcine skin is higher than the 200 N/m used in the present study.[30] The trajectories in FORCE suggested that the application of known forces to the mandibular incisor region and tracking jaw motion might be useful for estimating scar properties in clinical situations; jaw stiffness and muscle viscoelasticity have both been measured experimentally this way in the normal jaw, and successfully simulated by dynamic modeling.[31]

The difference between FORCE and OPEN trajectories can be explained by the primarily inferiorly directed force in the former, and the primarily oblique muscle forces in the latter. In OPEN, the bilateral articulation in CON reduced this lateral deviation, but did not eliminate it. Deviated jaw opening is a common clinical observation associated with muscle loss, and has functional implications with respect to mastication, since jaw closing must begin from the defect side, and the maximal intercuspal position approached mediolaterally. In the present study, wider incisal separations could have been reached with more muscle drive, and using additional muscles might have increased it further. More drive in the digastric and geniohyoid muscles, however, would have resulted in less lateral jaw deviation because these muscles have poor angles of attack, and their effectiveness diminishes as the jaw opens.[32]

Analysis of the biomechanical role of single muscles is a unique feature of computational modeling, since living subjects are unable to activate jaw muscles individually. Clinically unrealistic movements resulting from single-muscle activation in both models were, therefore, not surprising, but were helpful in revealing the actions of muscles likely contributing to mandibular instability. The marked rotation caused by RSM after molar contact in both models, and by RMT in NOCON, substantially explained clinical observations of frontal plane rotation. The tendency of RAT, RMT, RPT, and RDM to translate the jaw laterally, especially in a mandible without continuity, would normally be resisted by the temporomandibular ligament.[29] Continuous, or perhaps exclusive, use of such muscles may explain mandibular lateral displacement during occlusal contact sometimes observed clinically in mandibular resection patients without reconstruction.

The jaw instabilities demonstrated in UNIMOL partly explain the challenges for patients having to find new strategies of muscle contraction. Although the study did not determine the extent to which combined muscle use might provide stability, this concept could be tested by trial and error. A better alternative, however, might be to use inverse dynamic simulation to determine whether a given task is possible biomechanically, and if, so, whether it offers a foundation for motor retraining.

The generic models in the present study were limited by the absence of a tongue, a fixed hyoid apparatus, and arbitrary soft tissue forces. Objective measurements of jaw and tongue muscle activity, jaw and hyoid motion, and scar tissue properties are needed to expand such models, but are currently unavailable. It seems reasonable to assume that soft tissue pull would occur in the sectioned area of a mandible without continuity, but whether proximal forces limit motion near the angle of a grafted segment in the manner simulated here is left to debate. Also, all of the scar forces in the study were tensile, whereas some jaw movements could be restricted by soft tissue compression. Clinical measurements defining the physical effects of scarring on jaw movements would be helpful.

Comprehensive definition of the functional parameters would expand the scope of this type of investigation. Although the current iteration of the ArtiSynth platform is capable of integrating tongue, hyoid, and soft tissue mechanics, validation and future clinical application of patient-specific dynamic computer models require more precise descriptions of function than are presently available. At this preliminary exploratory stage, models such as those in this study are best viewed as hypothetical rather than comprehensive representations of clinical reality.

CONCLUSIONS

Dynamic computer models have been shown to simulate jaw movements in compromised mandibles with and without continuity. Generic versions can disclose the functional consequences of missing components, external forces on the mandible, atypical muscle activation, and postoperative scarring.

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