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A dynamic model of jaw and hyoid biomechanics during chewing

A.G. Hannam[a,*], I. Stavness[b], J.E. Lloyd[c], S. Fels[b]

[a]Department of Oral Health Sciences, Faculty of Dentistry, The University of British Columbia, 2199 Wesbrook Mall, Vancouver, BC, Canada V6T 1Z3
[b]Department of Electrical and Computer Engineering, The University of British Columbia, Canada
[c]Department of Computer Sciences, The University of British Columbia, Canada

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Abstract

Our understanding of human jaw biomechanics has been enhanced by computational modelling, but comparatively few studies have addressed the dynamics of chewing. Consequently, ambiguities remain regarding predicted jaw-gapes and forces on the mandibular condyles. Here, we used a new platform to simulate unilateral chewing. The model, based on a previous study, included curvilinear articular guidance, a mobile hyoid apparatus, and a compressible food bolus. Muscles were represented by Hill-type actuators with drive profiles tuned to produce target jaw and hyoid movements. The cycle duration was 732 ms. At maximum gape, the lower incisor-point was 20.1 mm down, 5.8 mm posterior, and 2.3 mm lateral to its initial, tooth-contact position. Its maximum laterodeviation to the working-side during closing was 6.1 mm, at which time the bolus was struck. The hyoid's movement, completed by the end of jaw-opening, was 3.4 mm upward and 1.6 mm forward. The mandibular condyles moved asymmetrically. Their compressive loads were low during opening, slightly higher on the working-side at bolus-collapse, and highest bilaterally when the teeth contacted. The model's movements and the directions of its condylar forces were consistent with experimental observations, resolving seeming discordances in previous simulations. Its inclusion of hyoid dynamics is a step towards modelling mastication.

Keywords: Modelling; Jaw muscles; Chewing cycle

1. Introduction

Mastication is an essential function compromised by developmental abnormalities, oro-facial reconstruction, and stroke, (Sze et al., 2002; Curtis et al., 1997; Hamdy et al., 2000; Bakke et al., 2007). Its biomechanics however are not fully understood, though some insight has been gained from the principles governing jaw dynamics (see Palla et al., 1997; Langenbach and van Eijden, 2001; Koolstra, 2002; Gallo, 2005).

The average chewing cycle lasts about 0.7 s (Ahlgren, 1976). The movement trajectory of the lower incisor is nearly perpendicular to the dental occlusal plane (Gibbs and Lundeen, 1982; Ogawa et al., 1996) with inter-incisal gapes reaching 17–20 mm. On jaw-closing, the incisor region typically laterodeviates about 5 mm, then moves medially as the food bolus engaged (Ahlgren, 1976; Gibbs and Lundeen, 1982; Miller, 1991). The mandibular condyles' lateral translation is minimal (0.4–0.6 mm) during chewing and other tasks (Gibbs and Lundeen, 1982; Payne, 1997; Okano et al., 2002; Otake et al., 2002; Miyawaki et al., 2004; Huang et al., 2006). During bolus compression therefore, the jaw rotates around its ipsilateral condyle as the contralateral condyle returns to its articular fossa (Gibbs and Lundeen, 1982; Gallo et al., 2000, 2006; Palla et al., 2003; Gallo, 2005; Miyawaki et al., 2001).

Jaw movements during chewing are part of a kinetic chain, synchronising with rhythmical motions of the hyoid, tongue and soft-palate, (Hiiemae and Palmer, 2003; Matsuo et al., 2005). Studies in two-dimensions suggest the hyoid moves upwards and forwards relative to the occlusal plane, and returns to its initial position near the end of jaw-opening, (Hiiemae et al., 2002; Hiiemae and Palmer, 2003).

As jaw biomechanics are difficult to study directly, modelling has become an important investigative tool

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*Corresponding author. Tel.: +1 604 822 3750; fax: +1 604 822 3594.
E-mail address: ahannam@interchange.ubc.ca (A.G. Hannam).

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(van Eijden, 2000; Koolstra, 2002; Hannam, 2005; Koolstra and van Eijden, 1995, 1997, 1999, 2005; Peck and Hannam, 2007; van Eijden and Koolstra, 1998; Peck et al., 2000, 2002; Sanguineti et al., 1998; Hansma et al., 2006; Stavness et al., 2006; Leon et al., 2006; de Zee et al., 2007). Simulations of the chewing cycle are rare however. Langenbach and Hannam (1999) analysed muscle tensions and condylar forces in a forward-dynamic model with planar articular guidance, and a fixed hyoid apparatus. It produced less jaw-gape than is usual during chewing, and higher loads on the ipsilateral than on the contralateral condyle. Notably however, condylar movements during human chewing and lateral tooth-clenching suggest the contralateral condyle is the more-heavily loaded (Palla et al., 1997; Okano et al., 2002). The temporomandibular ligaments had little effect in the model, although they are believed to limit extreme jaw movements, (Koolstra and van Eijden, 1999; Langenbach and Hannam, 1999; Peck et al., 2000; Koolstra et al., 2001; Hansma et al., 2006).

Recently, we developed a forward-dynamic model of the jaw with a platform integrating multiple system components (Stavness et al., 2006; Fels et al., 2006; http://www.artisynth.org). Here, we used it to determine the muscle drive needed to create plausible motions of both the mandible and the hyoid during unilateral chewing. We then focused on the apparent conflict between condylar forces predicted in the previous model, and condylar movements seen experimentally. We postulated that differences in the timing, magnitudes and directions of forces generated during the compressive phase of chewing might explain the condylar movements observed *in vivo*.

2. Materials and methods

2.1. The model

We have described the generic model elsewhere (Stavness et al., 2006; see Fig. 1). Its cranial and mandibular meshes were derived from cone-beam CT images of an adult male (via Amira 4.0, Mercury Computer Systems Inc., Chelmsford, MA, USA) which provided sufficient information to locate, but not reconstruct, all model components. Consequently, CAD-designed meshes of the hyoid, thyroid, cricoid and teeth were imported, morphed and positioned to match respective tissue boundaries in the image set. The co-registered meshes shared a coordinate frame with axes orthogonal to the Frankfort horizontal plane and permitted identification of muscle, articular and dental landmarks. The jaw's inertial properties were based on Langenbach and Hannam (1999). The small masses (10, 24 and 23 g) and other inertial properties assigned to the hyoid, thyroid and cricoid were estimated from their mesh geometries (assuming uniform densities) since we expected their dynamics would be dominated by the stiffnesses and viscosities of the surrounding muscles. Jaw and hyoid motions were damped with rotational and translational constants, and thyrohyoid, cricothyroid and cricotracheal membranes were modelled with spring-meshes.

Each temporomandibular joint was modelled as a point coinciding with the anatomical centre of the condyle, and constrained by frictionless surfaces. Its superior movement was limited by a curvilinear surface which was flat mediolaterally, and progressively changed in inclination from posterior to anterior; at its posterior end, it angled 40° downward, while 1 cm further forward, it angled 15° downward relative to the horizontal plane. A planar surface perpendicular to this prevented any posterior movement of the point from its initial position, while a third planar constraint prevented lateral motion. Its medial movement was unconstrained. This arrangement allowed realistic translation and rotation of condylar anatomy, and estimation of a reaction force expressed through its centre. Bilateral dental contact was simulated with frictionless, planar constraints oriented 10° forward and downward at the lower first molars. A Lagrangian rigid-body constraint formulation was used to compute exact reaction forces at all constraining surfaces. An elastic, spherical "food bolus" (10 mm in diameter) was positioned between the right first molars, and collapsed when any applied force reached 30 N.

Muscle tensions were simulated with Hill-type actuators representing the right and left anterior, middle and posterior temporalis, deep and superficial masseter, medial pterygoid, superior and inferior lateral pterygoid, and anterior digastric muscles. Their cross-sectional areas, length-tension and velocity-tension functions were based on Langenbach and Hannam (1999) and Peck et al., (2000) as was the constant (40 N/cm^2) used to transform maximum muscle areas into maximum-possible tensions. As the properties of the laryngeal muscles are not well-described in the literature, we approximated their maximum tensions according to their differences in length and cross-sectional areas relative to the jaw muscles; thus, the sternohyoids were assigned maximum tensions of 50 N, the posterior digastrics and stylohoids 30 N, and the mylohyoids and geniohyoids, 20 N. The maximum possible tensions for all muscles in the study are shown in Table 1.

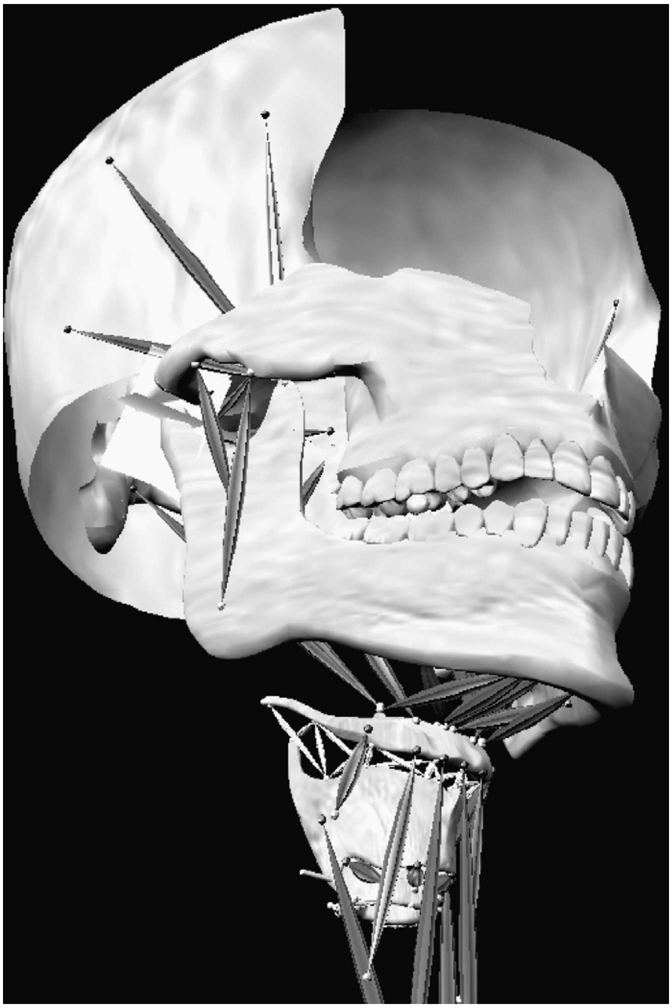

Fig. 1. Oblique view of the model. Control surfaces at the teeth and joints are semi-transparent. Sites of muscle attachment are indicated by spheres.

Table 1
Maximum and peak muscle tensions

Right muscles	Maximum tension (N)	Peak tension (N)	Left muscles	Maximum tension (N)	Peak tension (N)
RAT	158.0	30.0	LAT	158.0	26.9
RMT	95.6	22.0	LMT	95.6	16.3
RPT	75.6	11.3	LPT	75.6	12.1
RSM	190.4	32.4	LSM	190.4	30.5
RDM	81.6	13.1	LDM	81.6	7.3
RMP	174.8	28.0	LMP	174.8	24.5
RSP	17.0	1.02	LSP	17.0	0.68
RIP	50.0	5.0	LIP	50.0	4.5
RAD	50.0	5.0	LAD	50.0	4.5
RPD	30.0	1.2	LPD	30.0	1.2
RGH	20.0	1.8	LGH	20.0	1.8
RAM	20.0	1.6	LAM	20.0	1.8
RPM	20.0	1.6	LPM	20.0	1.8
RSH	30.0	2.4	LSH	30.0	2.4
RST	50.0	3.0	LST	50.0	4.0

Maxima for the right and left anterior temporals (RAT, LAT) middle temporals (RMT, LMT) posterior temporals (RPT, LPT) superficial masseters (RSM, LSM) deep masseters (RDM, LDM) medial pterygoids (RMP, LMP) superior lateral pterygoids (RSP, LSP) inferior lateral pterygoids (RIP, LIP) and anterior digastrics (RAD, LAD) were based on Langenbach and Hannam (1999). Maxima for the posterior digastrics (RPD, LPD) geniohyoids (RGH, LGH) anterior mylohyoids (RAM, LAM) posterior mylohyoids (RPM, LPM) stylohyoids RSH, LSH) and sternohyoids (RST, LST) were arbitrary. The peak tensions occurred at different times in the movement cycle.

2.2. *The Artisynth software platform*

The physics-based simulation used fourth-order Runge–Kutta integration in 0.1 ms timesteps. A graphical timeline depicted input and output probes. The input probes were time-referenced, cubic-spline functions ranging from zero to unity, the latter representing maximum muscle drive. These were shaped interactively, each function scaling the maximum tension assigned to its actuator. The output probes included incisor-point and condylar displacements, as well as bolus, dental, and condylar reaction forces. These were post-processed using Matlab (The Mathworks Inc., Natick, MA, USA).

2.3. *Simulations*

2.3.1. *Laterodeviation*

The model already attained 3 mm incisal separation at rest, and 50 mm separation at maximum jaw-gape, (Stavness et al., 2006). Prior to the chewing simulation, we also performed a right lateral jaw movement in the horizontal plane to ensure that the model would accommodate a chewing cycle. Simultaneous activation (sustained for 1 s at 10% of maximum drive) of all the right temporalis muscles and the deep masseter, plus the left superficial masseter, medial pterygoid, lateral pterygoid and mylohyoid, caused an incisor-point laterodeviation of 11.5 mm, i.e. similar to the 12 mm deviation reported in a comparable study by Koolstra and van Eijden, (1999).

2.3.2. *Chewing*

The target cycle's duration was 0.7 s (Ahlgren, 1976) with predetermined kinematic goals. During opening, we required initial motion of the incisor-point to the left, followed by an inter-incisal gape of 17–20 mm to the right. Viewed laterally, the opening and closing trajectories had to approximate a perpendicular to the occlusal plane. During early closing, the incisor's deviation to the right had to reach 5 mm, with an earlier return of the ipsilateral than of the contralateral condylar-point (Gallo, 2006). The hyoid's target trajectory included a midline, upward and forward excursion 3–5 mm, completed by the end of jaw-opening (Hiiemae et al., 2002).

Chewing was simulated by finding the muscle activation profiles needed to create the target incisor-point and hyoid trajectories within the specified time. Profile-shaping was guided by previous reports of muscle activation during unilateral chewing, (Moller, 1966; Hannam and Wood, 1981; Belser and Hannam, 1986; Wood et al., 1986), but required trial-and-error adjustments to reach the movement targets (Langenbach and Hannam, 1999). During jaw opening, the superior and inferior lateral pterygoid muscles were coactivated (Murray et al., 2004, 2007) as were the anterior and posterior digastric, geniohyoid and stylohyoid muscles. The infrahyoids were activated selectively to maintain the target hyoid trajectory. During early closing, the right anterior, middle and posterior temporalis, deep masseter, plus the left medial pterygoid and superficial masseter muscles were all active. During late closing, the right superficial masseter and medial pterygoid, plus the left temporalis group and deep masseter muscle also participated.

3. Results

3.1. *Jaw and hyoid displacement*

Frontal and lateral views of incisor-point motion are shown in Fig. 2, and time-referenced motion of the incisor-point, condylar-points and hyoid are found in Fig. 3. The total cycle duration was 732 ms. Jaw-opening lasted 335 ms, followed by a closing phase of 217 ms, and a dental "dwell" phase of 180 ms. At maximum gape, the incisor-point was 20.1 mm downward, 5.8 mm posterior, and 2.3 mm to the right of its initial position. During closing, its maximum lateral excursion was 6.1 mm. When the ipsilateral condylar-point returned to its initial position, the contralateral one remained 3.4 mm downward, 6.4 mm forward, and 0.3 mm medial. These differences are evident in Fig. 3.

The bolus was struck 459 ms after onset of the cycle, i.e. when the incisor point was 14.5 mm downward, 4.6 mm posterior, and 6.1 mm lateral. Medial jaw deviation occurred throughout bolus compression, and ceased on tooth contact.

The hyoid's midline upward (3.4 mm) and forward (1.6 mm) movements were completed before the jaw reached maximum gape. During jaw closure, and from bolus strike to dental contact, there was minimal deviation from its initial resting position.

3.2. *Muscle activation*

All muscle excitation profiles are shown in Fig. 4. The activation needed in the jaw-opening muscles was substantially less than in muscles used to crush the bolus. Asymmetrical activity in the mylohyoid and lateral pterygoid muscles was needed for the jaw to reach its lateral target locations during late opening and closing.

During early closing, asymmetrical drive in the closing muscles returned the ipsilateral condylar-point before the contralateral one. During late-closing, the closer muscles combined with the superior surface constraints to return

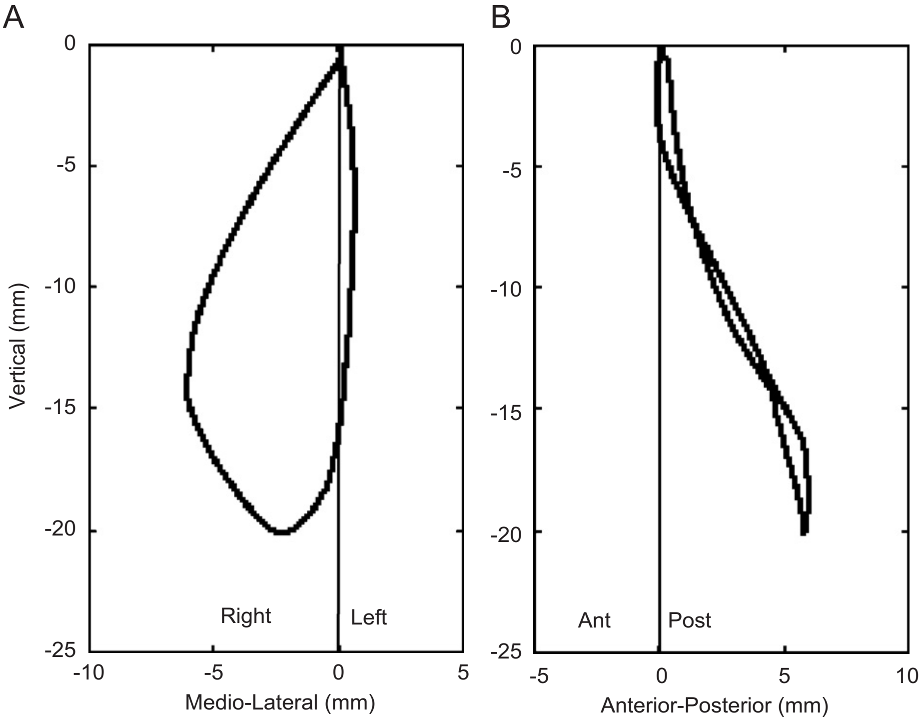

Fig. 2. Frontal (A) and lateral (B) views of incisor-point displacement. The figures are referenced to the Frankfort horizontal plane.

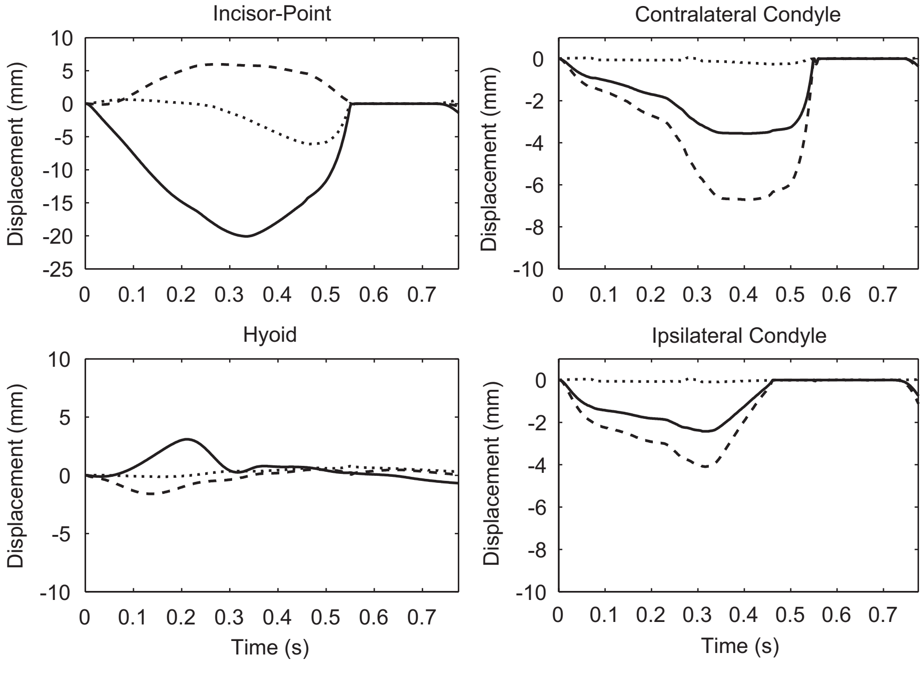

Fig. 3. Time-referenced displacement of the incisor-point, hyoid, and mandibular condyles. Vertical (solid lines) lateral (dotted lines) and antero-posterior movements (hatched lines) are plotted. In the lateral traces downward deflection is to the right. In the anterior–posterior traces downward deflection is forward.

both condylar-points to their starting positions before bolus collapse. Working-side lateral pterygoid activity was needed to slow otherwise-premature backward motion of the ipsilateral condylar-point during closing, while prolonged activity in the contralateral lateral pterygoid was required to delay the return of the condylar-point on that side. The timing of lateral pterygoid activity (albeit at low amplitudes) was therefore a critical factor in controlling laterodeviation during jaw-closure and bolus compression.

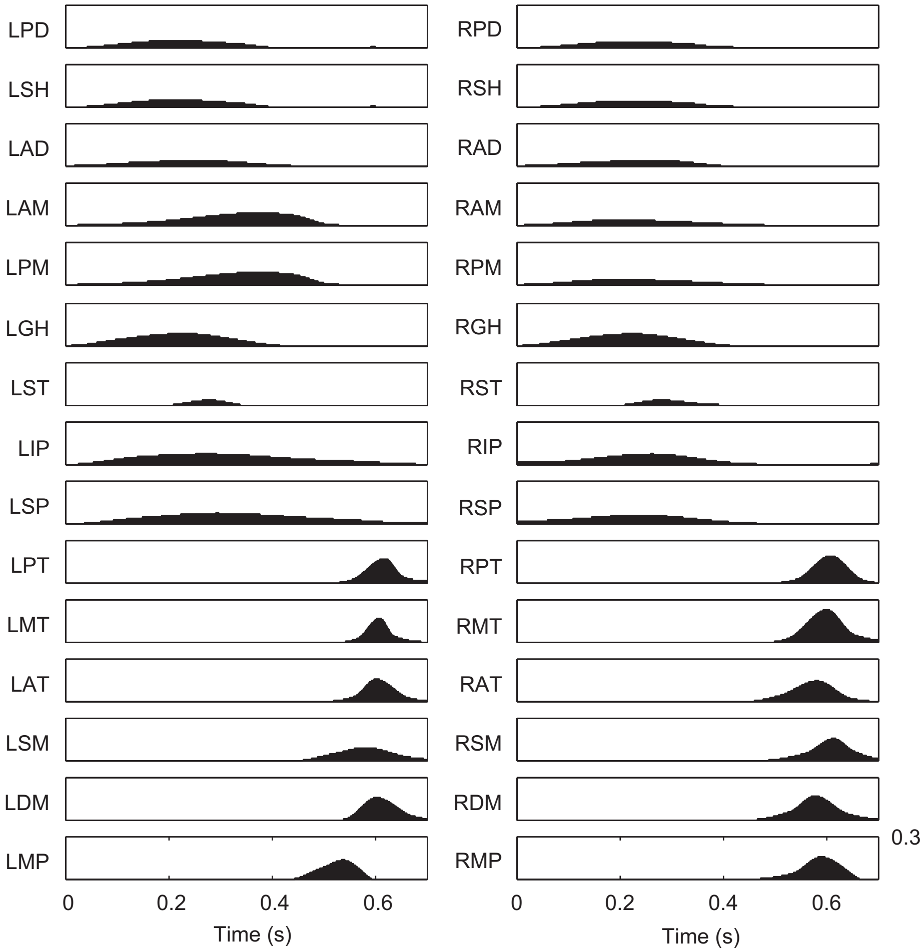

Fig. 4. Time-referenced muscle excitation profiles. All vertical axes are scaled relative to unity (maximum drive) similar to that on the lower right. Muscle abbreviations are as for Table 1.

Hyoid movement during opening was sensitive to posterior digastric, stylohoid and sternohyoid activation. The former muscles had a strong effect on its antero-posterior movement, while sternohyoid activity affected its vertical motion.

Peak muscle tensions associated with the excitation profiles in Fig. 4 are found in Table 1. To position the hyoid during jaw-opening, less peak tension was required in the posterior than in the anterior digastric. The highest opening tensions (3–5 N) occurred in the inferior lateral pterygoid and sternohyoid muscles. During jaw-closing, peak tensions were high in all the jaw-elevator muscles, especially on the working-side.

3.3. Condylar forces

During jaw-opening, top-surface reaction forces at both condylar-points were low, increasing substantially when the bolus was crushed, and on dental contact (Fig. 5).

During bolus compression, the top-surface reaction force at the contralateral condylar point was higher than that ipsilaterally. At bolus fracture, the overall resultant force on the contralateral side was 24.4 N, directed downwards and backwards. No lateral force occurred on this side during jaw-closing or bolus compression. The corresponding resultant at the ipsilateral condylar point was 29 N, directed downward, slightly forward and medially relative to the Frankfort horizontal and midline planes. After bolus fracture, i.e. when the teeth contacted, and both "condyles" were "seated", the highest top-surface force transferred to the ipsilateral side (Fig. 5).

4. Discussion

4.1. Model limitations

Actuators allow functional differentiation, but do not reflect the complex pennation and compartmentalisation in the jaw muscles; nor are they ideal analogues for curvilinear muscles like the mylohyoid (see van Eijden and Koolstra, 1998). We did not attempt to model the anatomy of the articular interface since the joint's composite structure and varying physical properties require sophisticated approaches such as dynamic, non-linear finite-element analysis. Other limitations included simplified

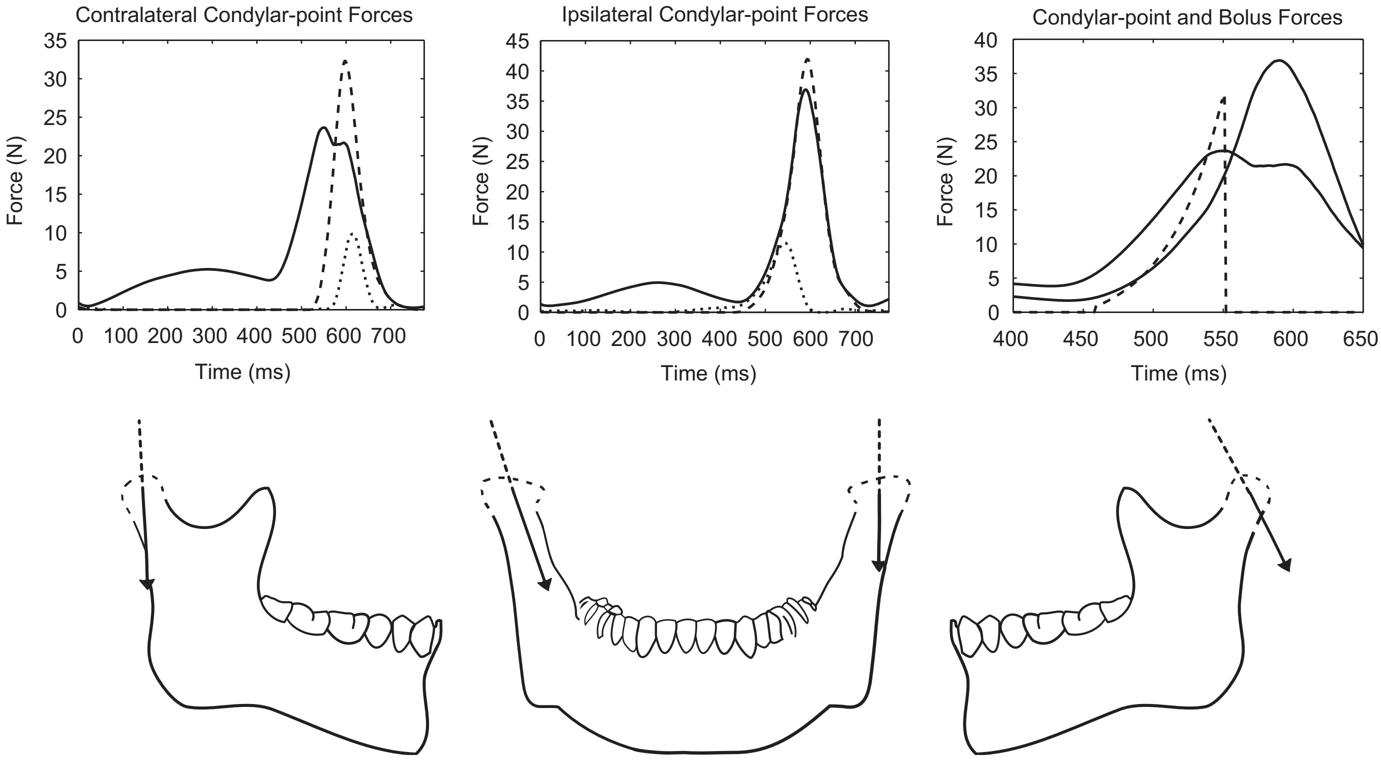

Fig. 5. The upper panels show condylar-point and bolus forces plotted against time (note that the vertical scales differ). Forces at the condylar-points from top-surface constraints are shown as solid lines. Forces due to lateral constraints are shown as dotted lines, and those from posterior constraints by hatched lines. The right-hand panel has an expanded timebase showing the same contralateral and ipsilateral top-surface forces (solid lines) as well as the force during bolus compression and collapse (hatched line). The lower panels depict reaction force vectors at the condylar points (solid arrows) upon bolus collapse. The magnitudes of the resultants were 24.4 and 29 N for the contralateral and ipsilateral condyles, respectively. Condylar shapes and resultant lines-of-action (dotted lines) indicate likely directions of joint compression.

tooth guidance and bolus properties, sparse representation of the infra-hyoid muscles, and omission of the tongue.

Models of the human jaw are difficult to validate (Hannam, 2005; Leon et al., 2006; Peck and Hannam, 2007; de Zee et al., 2007) since detailed exploration of the muscles and joints is restricted technically and ethically. Like others, our model is at best a working hypothesis strengthened by its performance of tasks with outcomes falling within normal ranges (Hannam, 2005; Peck and Hannam, 2007).

4.2. *Jaw and hyoid movements*

We believe this is the first model to show correlated jaw and hyoid movements during chewing. Its incisor-point, condylar-point and hyoid movements closely matched targets based on experimental studies by Ahlgren, (1976), Gallo, (2005), Gibbs and Lundeen, (1982), Hiiemae and Palmer (2003), Gallo et al., (2000, 2006), Hiiemae et al., (2002) and Palla et al., (2003). Also, its condylar-point movements were consistent with observed condylar motions during chewing (Gallo et al., 2000). Although the ipsilateral “condyle” had not quite returned to its initial position when the bolus was struck, it did so by the end of bolus collapse, about 100 ms later; thus, bolus compression mostly occurred during movement of the chewing-side teeth upwards and medially, while the contralateral “condyle” was returning to its initial position. The model’s hyoid motion was also consistent with *in vivo* descriptions, although some muscles were omitted, and the digastrics did not pass through a hyoidal sling. Our simulation of the infra-mandibular biomechanics, although producing a realistic result, therefore remains incomplete.

The jaw’s range of motion was greater, and the food bolus thicker, than in the Langenbach and Hannam (1999) model. The increased gape conformed to the chewing parameters reported by Ahlgren, (1976), while the larger bolus reflected the correlation between jaw-gape and bolus size, (Miyawaki et al., 2000). The force required to crush the bolus was half that used by Langenbach and Hannam, (1999) but remained within the normal range for human chewing; the average force on a single molar during peanut chewing is 57.7 N ± 35.7 for example (Kawata et al., 2007).

4.3. *Muscle excitation*

While the muscle excitation profiles we used may not be unique, they enabled the model to meet its targets. The tensions that resulted were the products of assumed constants, which, if inappropriate, would have been modified by compensatory changes in muscle-drive amplitudes. The peak tensions therefore provide a better estimate of the differential muscle-contraction amplitudes actually needed by the model.

The anterior digastric, posterior digastric, geniohyoid and stylohyoid muscles were co-activated because we were unable to find experimental data to the contrary. Our co-activation of the superior and inferior pterygoid muscles was based on recent evidence provided by Murray et al. (2007).

Asymmetric activation of both the lateral pterygoid and mylohyoid muscles was required to effect jaw laterodeviation during closing. These muscles produce horizontal torque, but do not encourage jaw-closure. Complex interactions among torques and forces can occur during jaw movements (Koolstra and van Eijden, 1999). Elevator muscle action encouraged retrusion of both condylar-points in the steeper sections of superior-surface guidance, while lateral pterygoid activation was needed to "brake" posterior motion of the condylar-point during late-closing. This was not required at wide gape, where the superficial masseter (our most anteriorly-oriented actuator; and see van Spronsen et al., 1997) had an improved angle-of-attack, and helped reduce condylar-point retrusion. It is likely there are associations among functional articular guidance, fibre-orientations in the superficial masseter, and perhaps in the medial pterygoid. Differential activation of obliquely oriented fibres in their posterior regions would help control the rate of condylar return over a wider range of incisal separation than in our model.

4.4. Jaw forces

The model's condylar-point forces until bolus collapse are consistent with observations of condylar movement during chewing (Palla et al., 1997; Okano et al., 2002) which suggest that the contralateral articulation is more-heavily loaded. If passive resistance from the articular fossae, condyles and discs created reaction forces in line with the force vectors we estimated here, compressive stresses would be greatest on the ipsilateral condyle's superior and lateral surfaces. In contrast, the contralateral condyle's compressive stress would likely occur on its superior aspect, causing a small upward condylar movement. Significantly, higher loading of the contralateral "condyle" is also evident in the Langenbach and Hannam (1999) report during actual bolus compression. The two models differ, however, in the magnitudes of "condylar" loads during opening, and on the contralateral "condyle" during closing. Both were lower in the present study.

Our prediction of higher peak loading on the ipsilateral condylar-point after bolus collapse agrees with Langenbach and Hannam's (1999) findings. Since the forces due to our model's top and back surfaces were nearly equal, articular compression during full dental contact would approximate a perpendicular to the Frankfort horizontal plane.

Changing bolus locations and properties would alter muscle drive patterns and articular reaction forces during natural chewing. Also, since static models have shown that bite-force direction can influence articular forces (Iwasaki et al., 2004), chewing with cusped teeth may produce different condylar forces than those estimated here for a flat dentition.

Conflict of interest

This is to certify that none of the authors of the manuscript entitled "A Dynamic Model of Jaw and Hyoid Biomechanics during Chewing" have conflicts of interest as described by the Instructions to Authors for the Journal of Biomechanics.

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References

Ahlgren, J., 1976. Masticatory movements in man. In: Anderson, D.J., Matthews, B. (Eds.), Mastication. Wright, Bristol, pp. 119–130.

Bakke, M., Moller, E., Thomsen, C.E., Dalager, T., Werdelin, L.M., 2007. Chewing in patients with severe neurological impairment. Archives of Oral Biology 52, 399–403.

Belser, U.C., Hannam, A.G., 1986. The contribution of the deep fibers of the masseter muscle to selected tooth-clenching and chewing tasks. Journal of Prosthetic Dentistry 56, 629–635.

Curtis, D.A., Plesh, O., Miller, A.J., Curtis, T.A., Sharma, A., Schweitzer, R., Hilsinger, R.L., Schour, L., Singer, M., 1997. A comparison of masticatory function in patients with or without reconstruction of the mandible. Head and Neck 19, 287–296.

de Zee, M., Dalstra, M., Cattaneo, P.M., Rasmussen, J., Svensson, P., Melsen, B., 2007. Validation of a musculo-skeletal model of the mandible and its application to mandibular distraction osteogenesis. Journal of Biomechanics 40, 1192–1201.

Fels, S., Vogt, F., van den Doel, K., Lloyd, J., Stavness, I., Vatikiotis-Bateson, E., 2006. ArtiSynth: a biomechanical simulation platform for the vocal tract and upper airway. Technical Report. Computer Science Department, The University of British Columbia, TR-2006-10.

Gallo, L.M., 2005. Modeling of temporomandibular joint function using MRI and jaw-tracking technologies-mechanics. Cells Tissues and Organs 180, 54–68.

Gallo, L.M., Fushima, K., Palla, S., 2000. Mandibular helical axis pathways during mastication. Journal of Dental Research 79, 1566–1572.

Gallo, L.M., Brasi, M., Ernst, B., Palla, S., 2006. Relevance of mandibular helical axis analysis in functional and dysfunctional TMJs. Journal of Biomechanics 39, 1716–1725.

Gibbs, C.H., Lundeen, H.C., 1982. Jaw movements and forces during chewing and swallowing and their functional significance. In: Lundeen, H.C., Gibbs, C.H. (Eds.), Advances in Occlusion. John Wright, Boston, USA, pp. 2–32.

Hamdy, S., Rothwell, J.C., Aziz, Q., Thompson, D.G., 2000. Organization and reorganization of human swallowing motor cortex: implications for recovery after stroke. Clinical Science 98, 151–157.

Hannam, A.G., 2005. The Biomechanical–biological Interface and its Significance in Oral Disease. In: Watanabe, M., Takahashi, N., Takada, H. (Eds.), Interface Oral Health Science, International Congress Series. Elsevier, pp. 3–10.

Hannam, A.G., Wood, W.W., 1981. Medial pterygoid activity during the closing and compressive phases of human mastication. American Journal of Physical Anthropology 55, 359–367.

Hansma, H.J., Langenbach, G.E.J., Koolstra, J.H., van Eijden, T.M.G.J., 2006. Passive resistance increases differentially in various jaw displacement directions. Journal of Dentistry 34, 491–497.

Hiiemae, K.M., Palmer, J.B., 2003. Tongue movements in feeding and speech. Critical Reviews in Oral Biology and Medicine 14, 413–429.

Hiiemae, K.M., Palmer, J.B., Medicis, S.W., Hegener, J., Jackson, B.S., Lieberman, D.E., 2002. Hyoid and tongue surface movements in speech and feeding. Archives of Oral Biology 47, 11–27.

Huang, B.Y., Whittle, T., Peck, C.C., Murray, G.M., 2006. Ipsilateral interferences and working-side condylar movements. Archives of Oral Biology 51, 206–214.

Iwasaki, L.R., Thornton, B.R., McCall, W.D., Nickel, J.C., 2004. Individual variations in numerically modeled human muscle and temporomandibular joint forces during static biting. Journal of Orofacial Pain 18, 235–245.

Kawata, T., Yoda, N., Kawaguchi, T., Kuriyagawa, T., Sasaki, K., 2007. Behaviours of three-dimensional compressive and tensile forces exerted on a tooth during function. Journal of Oral Rehabilitation 34, 259–266.

Koolstra, J.H., 2002. Dynamics of the human masticatory system. Critical Reviews in Oral Biology and Medicine 13, 366–376.

Koolstra, J.H., van Eijden, T.M.G.J., 1995. Biomechanical analysis of jaw closing movements. Journal of Dental Research 74, 1564–1570.

Koolstra, J.H., van Eijden, T.M., 1997. The jaw open-close movements predicted by biomechanical modeling. Journal of Biomechanics 30, 943–950.

Koolstra, J.H., van Eijden, T.M.G.J., 1999. Three-dimensional dynamical capabilities of the human masticatory muscles. Journal of Biomechanics 32, 145–152.

Koolstra, J.H., van Eijden, T.M., 2005. Combined finite-element and rigid-body analysis of human jaw joint dynamics. Journal of Biomechanics 38, 2431–2439.

Koolstra, J.H., Naeije, M., van Eijden, T.M.G.J., 2001. The three-dimensional active envelope of jaw border movement and its determinants. Journal of Dental Research 80, 1908–1912.

Langenbach, G.E.J., Hannam, A.G., 1999. The role of passive muscle tensions in a three-dimensional dynamic model of the human jaw. Archives of Oral Biology 44, 557–573.

Langenbach, G.E.J., van Eijden, T.M.G.J., 2001. Mammalian feeding motor patterns. American Zoologist 41, 1338–1351.

Leon, L.M.M., Liebgott, B., Agur, A.M., Norwich, K.H., 2006. Computational model of the movement of the human muscles of mastication during opening and closing of the jaw. Computer Methods in Biomechanics and Biomedical Engineering 9, 387–398.

Matsuo, K., Hiiemae, K.M., Palmer, J.B., 2005. Cyclic motion of the soft palate in feeding. Journal of Dental Research 84, 39–42.

Miyawaki, S., Ohkochi, N., Kawakami, T., Sugimura, M., 2000. Effect of food size on the movement of the mandibular first molars and condyles during deliberate unilateral mastication in humans. Journal of Dental Research 79, 1525–1531.

Miyawaki, S., Tanimoto, Y., Kawakami, T., Sugimura, M., Takano-Yamamoto, T., 2001. Motion of the human mandibular condyle during mastication. Journal of Dental Research 80, 437–442.

Miyawaki, S., Tanimoto, Y., Araki, Y., Katayama, A., Kuboki, T., Takano-Yamamoto, T., 2004. Movement of the lateral and medial poles of the working condyle during mastication in patients with unilateral posterior crossbite. American Journal of Orthodontics and Dentofacial Orthopedics 126, 549–554.

Miller, A.J., 1991. Craniomandibular Muscles: Their Role in Function and Form. CRC Press, Boca Raton, FL.

Moller, E., 1966. The chewing apparatus: an electromyographic study of the action of the muscles of mastication and its correlation to facial morphology. Acta Physiologica Scandinavica 69 (Suppl. 280), 1–229.

Murray, G.M., Phanachet, I., Uchida, S., Whittle, T., 2004. The human lateral pterygoid muscle; a review of some experimental aspects and possible clinical relevance. Australian Dental Journal 49, 2–8.

Murray, G.M., Bhutada, M., Peck, C.C., Phanachet, I., Sae-Lee, D., Whittle, T., 2007. The human lateral pterygoid muscle. Archives of Oral Biology 52, 377–380.

Ogawa, T., Koyano, K., Suetsugu, T., 1996. The relationship between inclination of the occlusal plane and jaw closing path. Journal of Prosthetic Dentistry 76, 576–580.

Okano, N., Baba, K., Akishige, S., Ohyama, T., 2002. The influence of altered occlusal guidance on condylar displacement. Journal of Oral Rehabilitation 29, 1091–1098.

Otake, T., Mayanagi, A., Tsuruta, J., Nozawa, K., Miura, H., Hasegawa, S., 2002. The role of posterior guidances under the altered anterior guidance. Journal of Oral Rehabilitation 29, 1196–1205.

Palla, S., Krebs, M., Gallo, L.M., 1997. Jaw tracking and temporomandibular joint animation. In: McNeill, C. (Ed.), Science and Practice of Occlusion. Quintessence Publishing, Chicago, IL, pp. 365–378.

Palla, A., Gallo, L.M., Grossi, D., 2003. Dynamic stereometry of the temporomandibular joint. Orthodontics and Craniofacial Research 6 (Suppl. 1), 37–47.

Payne, J.A., 1997. Condylar determinants in a patient population: electronic pantograph assessment. Journal of Oral Rehabilitation 24, 157–163.

Peck, C.C., Hannam, A.G., 2007. Human jaw and muscle modeling. Archives of Oral Biology 52, 300–304.

Peck, C.C., Langenbach, G.E.J., Hannam, A.G., 2000. Dynamic simulation of muscle and articular properties during human wide jaw opening. Archives of Oral Biology 45, 963–982.

Peck, C.C., Sooch, A.S., Hannam, A.G., 2002. Forces resisting jaw displacement in relaxed humans: a predominantly viscous phenomenon. Journal of Oral Rehabilitation 29, 151–160.

Sanguineti, V., Laboissiere, R., Ostry, D.J., 1998. A dynamic biomechanical model for neural control of speech production. Journal of the Acoustical Society of America 103, 1615–1627.

Stavness, I., Hannam, A.G., Lloyd, J.E., Fels, S., 2006. An integrated dynamic jaw and laryngeal model constructed from CT data. In: Proceedings of the International Symposium for Biomedical Simulation (ISBMS06). Springer LNCS 4072, pp. 169–177.

Sze, R.W., Paladin, A.M., Lee, S., Cunningham, M.L., 2002. Hemifacial microsomia in pediatric patients: asymmetric abnormal development of the first and second branchial arches. American Journal of Roentgenology 178, 1523–1530.

van Eijden, T.M.G.J., 2000. Biomechanics of the mandible. Critical Reviews of Oral Biology and Medicine 11, 123–136.

van Eijden, T.M.G.J., Koolstra, J.H., 1998. A model for mylohyoid muscle mechanics. Journal of Biomechanics 31, 1017–1024.

van Spronsen, P.H., Koolstra, J.H., van Ginkel, F.C., Weijs, W.A., Valk, J., Prahl-Andersen, B., 1997. Relationships between the orientation and moment arms of the human jaw muscles and normal craniofacial morphology. European Journal of Orthodontics 19, 313–328.

Wood, W.W., Takada, K., Hannam, A.G., 1986. The electromyographic activity of the inferior part of the human lateral pterygoid muscle during clenching and chewing. Archives of Oral Biology 31, 245–253.