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Modeling the Biomechanics of Swine Mastication – An Inverse Dynamics Approach

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Abstract

A novel reconstructive alternative for patients with severe facial structural deformity is Le Fort-based, face-jaw-teeth transplantation (FJTT). To date, however, only ten surgeries have included underlying skeletal and jaw-teeth components, all yielding sub-optimal results and a need for a subsequent revision surgery, due to size mismatch and lack of precise planning. Numerous studies have proven swine to be appropriate candidates for translational studies including pre-operative planning of transplantation. An important aspect of planning FJTT is determining the optimal muscle attachment sites on the recipient's jaw, which requires a clear understanding of mastication and bite mechanics in relation to the new donated upper and/or lower jaw. A segmented CT scan coupled with data taken from literature defined a biomechanical model of mandible and jaw muscles of a swine. The model was driven using tracked motion and external force data of one cycle of chewing published earlier, and predicted the muscle activation patterns as well as temporomandibular joint (TMJ) reaction forces and condylar motions. Two methods, polynomial and min/max optimization, were used for solving the muscle recruitment problem. Similar performances were observed between the two methods. On average, there was a mean absolute

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error (MAE) of <0.08 between the predicted and measured activation levels of all muscles, and an MAE of <7N for TMJ reaction forces. Simulated activations qualitatively followed the same patterns as the reference data and there was very good agreement for simulated TMJ forces. The polynomial optimization produced a smoother output, suggesting that it is more suitable for studying such motions. Average MAE for condylar motion was 1.2mm, which reduced to 0.37mm when the input incisor motion was scaled to reflect the possible size mismatch between the current and original swine models. Results support the hypothesis that the model can be used for planning of facial transplantation.

Keywords

Jaw Biomechanics; Swine Mastication; Craniomaxillofacial Surgery; Inverse Dynamics

1. Introduction

Le Fort-based, face-jaw-teeth (craniomaxillofacial) transplantation (FJTT) is a challenging procedure during which both hard and soft tissues taken from a cadaveric donor replace damaged portions of a recipient's face and underlying skeleton. A variety of different parameters need to be considered to obtain an optimal outcome for this type of surgery, including aesthetics and cephalometric measures in relation to donor-to-recipient discrepancies, as well as optimum teeth occlusion (Gordon et al., 2011; Gordon et al., 2012). Computer-assisted systems that use patient-specific models can provide the necessary tools for surgical pre-operative planning with the salient features of the outcome in mind. We have recently reported the results of our computer-assisted planning and execution (CAPE) system for FJTT surgery that uses pre-operative CT scans and planning along with optical tracking and custom-made guides to help the surgeon perform the transplantation (Gordon et al., 2013 and Gordon et al., 2014).

An important aspect of a FJTT surgery is that it requires precise planning to determine the expected changes related to masticatory muscles affecting both lower and upper jaws, the relationship between which could be different than that of the healthy recipient. The new occlusal plane angle, dento-facial relationships, and muscle insertions directly affect the way muscles are recruited for providing forces and motions for chewing or biting. Previous studies have identified swine as having analogous facial skeletal structures and actions of mastication compared to humans. Therefore, these characteristics make swine the ideal candidate for translational investigation of FJTT (Al Rakan et al., 2014; Farkas et al., 1976; Farkas et al., 1977; Papadaki et al., 2010; Santiago et al., 2014; Strom et al., 1986). However, further understanding of swine mastication and improved opportunities for translating the swine FJTT model to humans requires reliable models of swine jaw biomechanics (Hannam 2011).

Modeling human masticatory biomechanics has been the subject of extensive research. A majority of the computational models incorporate forward dynamics where muscle activations or forces are the known input and the resulting mandibular motion and the temporomandibular joint (TMJ) reaction forces are computed as the output (Stavness et al.,

2006). While useful for estimating outcomes such as mandibular motion or maximum bite force, this approach has the drawback of relying on the availability of individual muscle activations, which are difficult or impossible to acquire from every individual subject. Solving the inverse problem, on the other hand, can help better guide the FJTT reconstruction. A very important case is when the patient is missing one or more key masticatory muscles and thus the normal mandible motion and bite force have to be restored with a subset of original activators. This type of injury is commonly seen in wounded warriors and/or civilians with close-range, ballistic injuries to the face, head, and neck (Lew et al., 2010). Inverse dynamics can help identify muscle attachments so that, for a typical biting or chewing motion and force, muscle activations and/or TMJ reaction forces are minimized. In addition, solving the inverse problem can give insights regarding the working of the central nervous system (CNS) for either healthy individuals or patients with facial deformities (de Zee et al., 2007; Stavness et al., 2010).

The inverse dynamics problem deals with finding muscle/joint forces/torques, given the motion and external forces. Generally, solving the inverse problem is computationally less expensive than forward simulations, since motion (position and its derivatives) can be directly plugged into the equations of motion and the resultant joint forces can be computed without any need for integration over time (Erdemir et al., 2007). Finding individual muscle's contributions to the resultant forces, however, requires optimization, since most joints are redundantly activated, i.e., usually more than one muscle spans a joint. Two major groups of such solvers are forward dynamics-assisted and static optimizers. In the former, a set of initial muscle activations is used for solving the forward dynamics problem and the resulting motion and/or external forces are compared with the reference data. The optimizer then adjusts the muscle patterns so that the error is minimized (Koolstra & van Eijden, 2001; Hannam et al., 2008). In the latter, at each simulation time step, an optimization problem is solved that, based on muscle efforts, minimizes a (physiologically-related) function. Condylar joint load or muscle fatigue are among the popular such objective functions (Koolstra et al., 1988; May et al., 2001; Osborn & Baragar, 1985). This approach is computationally inexpensive and can be used for various sensitivity analyses (Erdemir et al., 2007) including optimizing muscle attachment sites for planning of FJTT surgery. Among other notable methods of optimization in masticatory dynamics is the method of Dynamic Geometric Optimization (DGO) used by Curtis et al., (2010) where muscles were activated based on their lines of action with respect to a specific tracked target point on the mandible of a lizard. They found good agreement between the results of their two dimensional simulations and electromyography (EMG) signals. A good review of the state of the art of masticatory biomechanics modeling is done by Curtis (2011).

Recently there have been efforts in creating software solutions dedicated to forward or inverse dynamics simulations of biomechanical motions, including masticatory dynamics. These include open-source platforms such as ArtiSynth (Lloyd et al., 2012) and OpenSim (Delp et al., 2007), and commercial software such as AnyBody (Damsgaard et al., 2006). These have shown various levels of success in performing inverse dynamics analyses and predicting muscle patterns for human mastication (Stavness et al, 2010; Cadova & Gallo, 2013; de Zee et al., 2007), with the study of de Zee and colleagues the only one, to our knowledge, that included direct quantitative comparison between measured and predicted

activation patterns. A similar inverse analysis of swine mastication is, however, missing from the literature. Therefore, as a first step in planning FJTT for swine subjects, we created a biomechanical model of jaw and mastication, and used the simulation results of previous forward dynamics models to drive and verify the model. The following sections describe the model and the simulation as well as the results and their comparison with the reference data. A discussion about the implications of the model concludes the paper.

2. Methods

A musculoskeletal model of a swine skull, mandible and the mastication muscles was created using the proprietary software AnyBody (AnyBody Technology, Aalborg, Denmark). The model included bilateral jaw closers and openers as follows: superficial and deep masseter, anterior, medial, and posterior temporalis, medial and lateral pterygoid, and digastric, resulting in a total of 16 muscles (Figure 1). This arrangement was taken from the simulation studies of Langenbach and colleagues (Langenbach et al., 2002; Langenbach et al., 2006). Manual segmentation using commercial image processing software (Amira, Visualization Sciences Group, Burlington, MA; Mimics, Materialise, Plymouth, MI) defined surface representations of a 15kg miniature swine from computed tomography (CT) data. A SOMATOM Definition Flash scanner (Siemens Healthcare, Germany) obtained the CT data at a resolution of 0.45×0.45×0.60 mm. The musculoskeletal model included a rigidly fixed skull and a freely moving mandible. Modeling of the two TMJs follows that described by de Zee et al. (2007): the two TMJ points on the mandible were constrained to translate on a slanted plane, representative of the mandibular fossa, and both TMJs were free to rotate in all directions. This left the mandible with four degrees of freedom (DOFs). By analyzing the segmented surface representation of the mandible, the plane defining the TMJ motion was canted 15 degrees medially (Zhang, 2001). The inter-condylar distance was the same as that of the original study (72mm).

Muscles were modeled as Hill-type actuators (Zajac, 1989). Peak isometric forces were taken from the study of Langenbach et al. (2002), and the attachment sites were determined based on anatomical landmarks and published swine dissection studies (Herring & Scapino, 1973; Herring et al., 1984). Since the literature is limited regarding actual fiber/tendon ratios for most of swine mastication muscles, we defined 90% of the total muscle length at jaw close as optimum fiber length and the remainder as slack tendon length. This resulted in numbers similar to optimum lengths reported by Anapol and Herring for digastric and masseter (Anapol & Herring, 1989). At 5% tension, each muscle's tendon was assumed to provide a passive force equal to the maximum isometric fiber force (Langenbach et al., 2002). Muscle parameters are summarized in Table 1.

To prescribe motion and external forces, lower incisor and the bilateral first molars were manually identified on the surface model (Figure 1). The model was driven by the three DOF motion of the lower incisor recorded by Langenbach et al. (2002) as the output of their simulation (Figure 2). The remaining free DOF of the mandible was restricted by prohibiting the right (working) TMJ from lateral motion. Food crushing and teeth occlusal forces were also applied on the working side first molar (Langenbach et al., 2006). Mass and inertia of the mandible were set according to the reference study (Langenbach et al., 2002). Center of

mass was assumed as the geometrical center of the mandible surface model and the whole model was subjected to gravity in the vertical direction. The software then calculated the muscle activations and TMJ reaction forces as well as condylar motions in the anterior-posterior (A-P) direction. We examined two methods of forming the optimization problem: 3rd order polynomial (Crowninshield & Brand, 1981) and min/max (Rasmussen et al., 2001) muscle recruitment algorithms. The optimization problem can be summarized as Eq. 1:

$$\begin{aligned} \min g \quad & (F_i) \\ \text{s.t.} \quad & C\mathbf{f}=\mathbf{r} \\ & 0 \leq f_i \leq N_i, \quad i=1..m \end{aligned} \quad (1)$$

Here $f_i = aN_i$ is each muscle's force, N_i is the muscle's instantaneous strength (the maximum force muscle can provide at its current configuration if it is maximally excited), a is activation ($a \in [0,1]$), $\mathbf{f}$ is the vector of muscle and joint forces acting on the moving body (mandible), $\mathbf{r}$ is a vector representing the external and inertial forces, C is a matrix of coefficients, and m is the number of muscles moving the rigid body. The first constraint essentially ensures that the equations of motions hold for the rigid body. In the case of polynomial optimization, the objective function $g(F_i)$ can be written as

$$g(F_i) = \sum_{i=1}^m \left(\frac{F_i}{N_i} \right)^3, \text{ while for the min/max problem, the objective function takes the form } g(F_i) = \max \left(\frac{F_i}{N_i} \right), i=1 \dots m.$$

Simulated activation signals were compared with the reference data of Langenbach et al. (2002). For their study, they used indwelling wire electrodes to record EMG activities of mastication muscles and then fitted B-spline curves to the results. Comparison between those data and our simulation was performed by finding the mean absolute error (MAE) as proposed by de Zee et al. (2007) using Eq. 2.

$$MAE = \frac{1}{n} \sum_{i=1}^n |S_i - M_i| \quad (2)$$

Here M is the measured signal, S is the simulated signal, and n is the number of samples. The original study (Langenbach et al., 2002) reported only one set of activations for the temporalis muscle bundles so we averaged the simulated activation of the three temporalis muscles to compare with the reference data. Same method was used to compare the TMJ reaction force and A-P condyle motion profiles. Upon primary inspection, the A-P condyle motions deviated from the original simulation during jaw opening and we hypothesized a size mismatch to be the source of discrepancy. Therefore, the simulation was repeated with incisor motion that was scaled to 60% its original values and the A-P motion was recorded again.

3. Results

Figure 3 shows comparisons between the muscle activation patterns and Table 2 summarizes the MAE values. The average MAE was 0.077 (0.027-0.138) for polynomial and 0.074 (0.026-0.124) for min/max recruitment. All activations were sampled at 1ms intervals.

Similar qualitative patterns of activation can be seen between simulations and reference data for both recruitment methods, although min/max criteria produced some irregularities, e.g., for lateral pterygoid and digastric muscles. There was no statistical difference between left and right MAE results for either method ($P>0.79$).

Figure 4 depicts the comparison between the working and balancing side TMJ reaction forces. Very good overall agreement for the patterns can be observed. The average MAE was 6.6N in polynomial and 6.4N in min/max optimization. The min/max method resulted in a spike in TMJ reaction force for the left side, while polynomial optimization created smoother profiles in general.

Figure 5 shows the reference and simulated condylar motions. When unscaled data was used, the average MAE for two sides was 1.2mm (maximum 3.98mm), which reduced to 0.37 (maximum 1.19mm) when the incisor motion was scaled.

4. Discussion

Effective planning of FJTT requires a deep understanding of the underlying biomechanics of mastication. In the single-jaw scenario, i.e., transplantation of maxilla only, the hybrid combination of donor and recipient jaw-teeth segments will undoubtedly have significant discrepancies with premature interference. For instance, all single-jaw recipients performed to date have required some form of major revision surgery due to significant malocclusion (Gordon et al., 2011; Gordon et al., 2012). Reliable subject-specific biomechanical models may help plan such procedures through an understanding of the optimum muscle attachment sites and, ultimately, improve functional outcomes. Validating an inverse dynamics musculoskeletal model is a major undertaking and the several simplifying assumptions result in deviations from real scenarios. However, even when simplified, biomechanical models can provide valuable insights regarding the effect of muscle attachments on the outcome of the motion being studied.

In this paper we describe a musculoskeletal model of swine mastication containing several key jaw muscles. As a first verification step, the model was driven using the output of previous forward dynamics simulations (lower incisor motion and bite reaction forces) with the goal of predicting the simulation inputs (muscle activation levels) as well as TMJ reaction forces. Results showed good agreement for muscle recruitments with some discrepancies that could be related to the inevitable differences between reference and current model.

Among the likely sources of error could be the assumed muscle/fiber ratios that differed with the unknown ones of the reference simulations. We used a constant fiber/tendon length ratio for consistency and it is not currently known to us how manual adjustments to each individual muscle can improve the results. Nonetheless, the possibly improved ratios must be verified against experimental data of swine dissections. Also, muscle attachment points were found using anatomical landmarks on the surface representation and it is likely that the reference swine model had a different anatomy. Another source of error introduced into the model is the result of inaccuracies and noise in digitizing the motion plots that were used to

drive the model. Since position data is differentiated twice to estimate accelerations and find forces, small inaccuracies can result in considerable deviations from the source data.

During the opening phase, digastric muscles in our model were activated later than the ones in the reference data. Also, in the reference simulations, jaw closers were activated quicker during the upward movement of the mandible. Besides the possible differences in the jaw accelerations and center of mass locations, the force distributing algorithm in our simulation may have worked in a different way than the motor control system in the animal subject of the reference model. The lower jaw is one of the most redundantly mobilized joints in the body and the activating strategy of the central nervous system (CNS) for it is not completely understood. The simulations minimized the relative muscle force at each time step, which implies reduction of fatigue (Rasmussen et al., 2001). Although this has been shown to produce results that agree with biological data, in some human subjects/tasks, minimization of joint load has been shown to perform better (Iwasaki et al., 2003). Furthermore, gravity, seemingly, provided a large portion of the initial load required to open the jaw in the simulation and also the passive tension in the jaw closers contributed to pulling the mandible back up. This is in agreement with the findings of Koolstra and van Eijden (1997). One must also not forget the unmodeled passive resistance of soft tissue (skin, fat, etc.) surrounding the skeletal structure that affected the activation patterns recorded originally.

Comparing the performance of the two recruitment algorithms, the polynomial recruitment algorithm produced smoother outputs, which suggests that it should be preferred over the min/max criterion that was used before in similar simulations (de Zee et al., 2007). The min/max criterion can result in sudden peaks and discontinuities in the muscle activations, as observed here, if the studied motion involves rapid changes in the accelerations and/or muscle moment arms.

Simulated condylar reaction forces followed closely the reference forces. This further helps verify the inverse dynamics solver, which calculates the constraint reaction forces and the required muscle forces simultaneously. Large forces occur during food crushing/occlusion and those dominate the acceleration and inertial forces of the mandible, which are minimal during that time period. In this phase, quasi-static load balance occurs between all the forces acting on the mandible which include the muscle forces, TMJ reaction forces and external biting/occlusal forces. It is important to note that the transplanted maxilla, in the particular instance of single jaw transplantation, as compared to all other orthognathic surgical procedures, will be of different embryological origin and therefore provide an entire set of forces dissimilar to those experienced by the mandible originally. Therefore accurate modeling of those forces is of crucial importance.

Of note is also the difference between the ratio of working/balancing maximum loads between the swine and human models. Langenbach and Hannam (1999) simulated unilateral chewing and “chopping” motions of human mandible and found that, for a chewing movement, maximum condyle load in the working side is larger than that of the balancing side during occlusal. The opposite was observed in their chopping simulation and in our swine model, in agreement with the reference swine data. It must be noted that the lateral

movement of the swine mandible during chewing was much smaller than that of humans, so the swine unilateral chewing could be effectively more similar to human chopping.

The predicted A-P motion of the condyle deviated largely from the reference data in the opening phase and it then closely followed the reference data. This, we hypothesized, could be due to size mismatch between the original and current model. Scaling the input motion compensated for this error, which supports this assumption.

Understanding the similarities and differences in kinematics and kinetics between human and swine mastication can aid in better large-animal translational FJTT studies, which are warranted to improve outcomes and allow pre-clinical development of computer-assisted technologies for such surgeries (Al Rakan et al., 2014, Santiago et al., 2014). Among the similarities between swine and human mastication are both the range and profiles of condylar motion (Hannam et al., 2008). During early opening and early closing of the jaw, the balancing side rotates around the hinge-like working side TMJ and therefore has a larger range of A-P motion. The balancing condyle almost returns to its resting position right before the food crush, which is followed by complete return to the rest position by the working side condyle. An anatomical difference between humans and swine that affects the mastication mechanics is the arrangement of the temporalis muscle bundles. In swine, these fibers originate more posteriorly and therefore the line of action of these muscles has a larger horizontal component than the ones in humans. As a result, when these muscles are activated during food crushing, a force component pulls the mandible posteriorly so a counter-balancing force is required to stabilize the jaw. This is likely the source of lateral pterygoid activation, which is usually not seen in human mastication during food crushing (Hannam et al., 2008). However, these differences can be effectively modeled in the software, enabling translation of muscle optimization procedures on swine to humans for FJTT.

While specifically designed for FJTT, studies such as this have implications for a variety of other fields, including craniofacial surgery, oral-maxillofacial surgery, ear-nose-throat (ENT)/head and neck surgery, dentistry and comparative anatomy. For instance, studies of mammalian, reptile, or dinosaur jaw mechanics so far have mostly included forward dynamics simulations with the aim of predicting the maximum bite forces (Bates & Falkingham, 2012; Curtis et al., 2008; Moazen et al., 2008). Inverse dynamics simulations can help better understand the underlying motor control of biting and mastication and, in turn, feeding habits of such animals.

This study provided a first step verification of an inverse dynamics model of swine mastication compared to published data. There were several inevitable sources of discrepancy between the model and the published data of previous forward dynamics simulation. These can be alleviated if data, including EMG signals and incisor trajectories as well as the bony anatomy and muscle parameters, are gathered from the same specimen, which will be part of our future research. Another point of improvement is to add surface contact model between the lower and upper jaw, as opposed to simple point forces, which will help greatly in planning of transplant surgeries.

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References

- Al Rakan M, Shores J, Bonawitz S, Santiago G, Christensen J, Grant G, Murphy R, Basafa E, Armand M, Otovic P, Eller S, Brandacher G, Gordon C. Ancillary procedures necessary for translational research in experimental craniomaxillofacial surgery. *Journal of Craniofacial Surgery*. 2014 [In Press].
- Anapol F, Herring S. Length-Tension Relationships of Masseter and Digastric Muscles of Miniature Swine During Ontogeny. *Journal of Experimental Biology*. 1989; 143:1–16. [PubMed: 2732657]
- Bates K, Falkingham P. Estimating maximum bite performance in *Tyrannosaurus rex* using multi-body dynamics. *Biology Letters*. 2012; 8:660–664. [PubMed: 22378742]
- Cadova M, Gallo L. Is OpenSim suitable for masticatory system analysis? *Russian Journal of Biomechanics*. 2013; 17(3):53–67.
- Crowninshield R, Brand R. A physiologically based criterion of muscle force prediction in locomotion. *Journal of Biomechanics*. 1981; 14:793–801. [PubMed: 7334039]
- Curtis N, Jones M, Evans S, Shi J, O'Higgins P, Fagan M. Predicting muscle activation patterns from motion and anatomy: modelling the skull of *Sphenodon* (Diapsida: Rhynchocephalia). *Journal of The Royal Society Interface*. 2010; 7:153–160.
- Curtis N. Craniofacial biomechanics: an overview of recent multibody modelling studies. *Journal of Anatomy*. 2011; 218:16–25. [PubMed: 21062283]
- Curtis N, Kupczik K, O'Higgins P, Moazen M, Fagan M. Predicting Skull Loading: Applying Multibody Dynamics Analysis to a Macaque Skull. *The Anatomical Record*. 2008; 291:491–501. [PubMed: 18384061]
- Damsgaard M, Rasmussen J, Christensen S, Surma E, de Zee M. Analysis of musculoskeletal systems in the AnyBody Modeling System. *Simulation Modelling Practice and Theory*. 2006; 14:1100–1111.
- de Zee M, Dalstra M, Cattaneo P, Rasmussen J, Svensson P, Melsen B. Validation of a musculoskeletal model of the mandible and its application to mandibular distraction osteogenesis. *Journal of Biomechanics*. 2007; 40:1192–1201. [PubMed: 16930608]
- Delp S, Anderson F, Arnold A, Loan P, Habib A, John C, Guendelman E, Thelen D. OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement. *IEEE Transactions on Biomedical Engineering*. 2007; 54(11):1940–1950. [PubMed: 18018689]
- Erdemir A, McLean S, Herzog W, van den Bogert A. Model-based estimation of muscle forces exerted during movements. *Clinical Biomechanics*. 2007; 22:131–154. [PubMed: 17070969]
- Farkas L, Munro I, Vanderby B. Quantitative Assessment of the Morphology of the Pig's Head Used as a Model in Surgical Experimentation Part 1: Methods and Measurements. *Canadian Journal of Comparative Medicine*. 1976; 40:397–403. [PubMed: 1000401]

- Farkas L, James J, Vanderby B. Quantitative Assessment of the Morphology of the Pig's Head Used as a Model in Surgical Experimentation Part 2: Results of Measurements. *Canadian Journal of Comparative Medicine*. 1977; 41:455–59. [PubMed: 922561]
- Gordon C, Susarla S, Peacock Z, Cetrulo C, Zins J, Papay F, Kaban L, Yaremchuk M. Osteocutaneous maxillofacial allotransplantation: lessons learned from a novel cadaver study applying orthognathic principles and practice. *Plastic and reconstructive surgery*. 2011; 128:465e–479e.
- Gordon C, Susarla S, Peacock Z, Kaban L, Yaremchuk M. Le fort-based maxillofacial transplantation: Current state of the art and a refined technique using orthognathic applications. *Journal of Craniofacial Surgery*. 2012; 23:81–87. [PubMed: 22337380]
- Gordon C, Swanson E, Susarla S, Coon D, Rada E, Al Rakan M, Santiago G, Shores J, Bonawitz S, Fishman E, Murphy R, Armand M, Liacouras P, Grant G, Brandacher G, Lee W. Overcoming cross-gender differences and challenges in Le Fort-based, craniomaxillofacial transplantation with enhanced computer-assisted technology. *Annals of Plastic Surgery*. 2013; 71(4):421–428. [PubMed: 24025655]
- Gordon C, Murphy R, Coon D, Basafa E, Otake Y, Al Rakan M, Rada E, Susarla S, Swanson E, Fishman E, Santiago G, Brandacher G, Liacouras P, Grant G, Armand M. Preliminary development of a workstation for craniomaxillofacial surgical procedures: introducing a computer-assisted planning and execution system. *Journal of Craniofacial Surgery*. 2014; 25(1):273–83. [PubMed: 24406592]
- Hannam A. Current computational modelling trends in craniomandibular biomechanics and their clinical implications. *Journal of Oral Rehabilitation*. 2011; 38:217–234. [PubMed: 20819138]
- Hannam A, Stavness I, Lloyd J, Fels S. A dynamic model of jaw and hyoid biomechanics during chewing. *Journal of Biomechanics*. 2008; 41:1069–1076. [PubMed: 18191864]
- Herring S, Scapino R. Physiology of Feeding in Miniature Pigs. *Journal of Morphology*. 1973; 141(4): 427–460. [PubMed: 4760635]
- Herring S, Grimm A, Grimm B. Regulation of Sarcomere Number in Skeletal Muscle: A Comparison of Hypotheses. *Muscle & Nerve*. 1984; 7:161–173. [PubMed: 6717493]
- Iwasaki L, Petsche P, McCall W, Marx D, Nickel J. Neuromuscular objectives of the human masticatory apparatus during static biting. *Archives of Oral Biology*. 2003; 48:767–777. [PubMed: 14550379]
- Koolstra J, van Eijden T, Weijs W, Naeije M. A Three-Dimensional Mathematical Model of the Human Masticatory System Predicting Maximum Possible Bite Forces. *Journal of Biomechanics*. 1988; 21(7):563–576. [PubMed: 3410859]
- Koolstra J, van Eijden T. Dynamics of the Human Masticatory Muscles During A Jaw Open-Close Movement. *Journal of Biomechanics*. 1997; 30(9):883–889. [PubMed: 9302610]
- Koolstra J, van Eijden T. A method to predict muscle control in the kinematically and mechanically indeterminate human masticatory system. *Journal of Biomechanics*. 2001; 34:1179–1188. [PubMed: 11506788]
- Langenbach G, Hannam A. The role of passive muscle tensions in a three-dimensional dynamic model of the human jaw. *Archives of Oral Biology*. 1999; 44:557–573. [PubMed: 10414871]
- Langenbach G, Zhang F, Herring S, Hannam A. Modelling the masticatory biomechanics of a pig. *Journal of Anatomy*. 2002; 201:383–393. [PubMed: 12448773]
- Langenbach G, Zhang F, Herring S, van Eijden T, Hannam A. Dynamic mechanics in the pig mandibular symphysis. *Journal of Anatomy*. 2006; 209:69–78. [PubMed: 16822271]
- Lew T, Walker J, Wenke J, Blackburne L, Hale R. Characterization of craniomaxillofacial battle injuries sustained by United States service members in the current conflicts of Iraq and Afghanistan. *Journal of Oral and Maxillofacial Surgery*. 2010; 68:3–7. [PubMed: 20006147]
- Lloyd J, Fels S, Stavness I. ArtiSynth: A Fast Interactive Biomechanical Modeling Toolkit Combining Multibody and Finite Element Simulation. *Studies in Mechanobiology, Tissue Engineering and Biomaterials*. 2012; 11:355–394.
- May B, Saha S, Saltzman M. A three-dimensional mathematical model of temporomandibular joint loading. *Clinical Biomechanics*. 2001; 16:489–495. [PubMed: 11427291]

- Moazen M, Curtis N, Evans S, O'Higgins P, Fagan M. Rigid-body analysis of a lizard skull: Modelling the skull of *Uromastyx hardwickii*. *Journal of Biomechanics*. 2008; 41:1274–1280. [PubMed: 18308322]
- Osborn J, Baragar F. Predicted Pattern of Human Muscle Activity During Clenching Derived From A Computer Assisted Model: Symmetric Vertical Bite Forces. *Journal of Biomechanics*. 1985; 18(8): 599–612. [PubMed: 4055814]
- Papadaki M, Troulis M, Glowacki J, Kaban L. A Minipig Model of Maxillary Distraction Osteogenesis. *Journal of Oral and Maxillofacial Surgery*. 2010; 68(11):2783–2791. [PubMed: 20971370]
- Rasmussen J, Damsgaard M, Voigt M. Muscle recruitment by the min/max criterion – a comparative numerical study. *Journal of Biomechanics*. 2001; 34:409–415. [PubMed: 11182135]
- Santiago G, Susarla S, Al Rakan M, Coon D, Rada E, Sarhane K, Shores J, Bonawitz S, Cooney D, Sacks J, Murphy R, Fishman E, Brandacher G, Lee W, Liacouras P, Grant G, Armand M, Gordon C. Establishing Cephalometric Landmarks for the Translational Study of Le Fort-based Facial Transplantation in Swine: Enhanced applications using computer-assisted surgery and custom cutting guides. *Plastic & Reconstructive Surgery*. 2014 [Online First].
- Stavness, I.; Hannam, A.; Lloyd, J.; Fels, S. An Integrated Dynamic Jaw and Laryngeal Model Constructed from CT Data. In: Harders, M.; Szekely, G., editors. *Lecture Notes in Computer Science* 4072. Springer-Verlag; 2006. p. 169-177.
- Stavness I, Hannam A, Lloyd J, Fels S. Predicting muscle patterns for hemimandibulectomy models. *Computer Methods in Biomechanics and Biomedical Engineering*. 2010; 13(4):483–491. [PubMed: 20635264]
- Strom D, Holm S, Clemensson E, Haraldson T, Carlsson G. Gross Anatomy of the Mandibular Joint and Masticatory Muscles in the Domestic Pig. *Archives of Oral Biology*. 1986; 31(11):763–768. [PubMed: 3479064]
- Zajac F. Muscle and Tendon: Properties, Models, Scaling, and Application to Biomechanics and Motor Control. *Critical Reviews in Biomedical Engineering*. 1989; 17(4):359–410. [PubMed: 2676342]
- Zhang, F. PhD Thesis. University of British Columbia, BC; Canada: 2001. Biomechanics of the Mammalian Jaw.

Figure 1.

Graphical representation of the skull (left) and mandible and muscle attachments with the skull hidden (right). Muscle abbreviations are as follows: superficial (SM) and deep (DM) masseter, anterior (AT), medial (MT), and posterior (PT) temporalis, medial (MP) and lateral (LP) pterygoid, and digastric (DG). Coordinate frames represent the TMJs, first molars, and lower and upper incisors. Red frames are attached to the mandible (moving body) and green frames are attached to the skull (fixed body).

Figure 2.

Left: three-dimensional motion of the lower incisor. Right: external load (i.e., bite force) acting on the working side first molar.

Figure 3.
Simulated and reference (EMG) activation profiles.

Figure 4.

Comparisons between the results of original (Langenbach et al., 2006) and current simulations of TMJ reaction forces.

Figure 5.

Comparisons between the results of original (Langenbach et al., 2002) and current simulations of A-P condyle motions. “Unscaled Motion” represents the results of using the original digitized incisor motion while “Scaled Motion” denotes the results of simulation using the 60% scaled incisor motion.

Table 1

Muscle parameters

Muscle	Optimum Fiber Length (cm)	Maximum Force at Optimum Length (N)
Superficial Masseter	5.4	304.4
Deep Masseter	3.8	188.8
Anterior Temporalis	5.0	64.8
Medial Temporalis	3.9	73.2
Posterior Temporalis	2.9	73.2
Medial Pterygoid	3.4	226.8
Lateral Pterygoid	2.9	100.4
Digastric	5.5	56.4

Table 2

Mean absolute error for the muscle activations. Simulated activations of anterior, medial, and posterior temporalis muscles were averaged and compared against the reference data. Poly and min/max refer to polynomial and min/max recruitment algorithms, respectively.

Muscle	Left		Right	
	Poly	Min/Max	Poly	Min/Max
Superficial Masseter	0.070	0.063	0.042	0.04
Deep Masseter	0.115	0.112	0.113	0.113
Temporalis	0.065	0.062	0.050	0.049
Medial Pterygoid	0.048	0.049	0.027	0.026
Lateral Pterygoid	0.089	0.081	0.138	0.124
Digastric	0.075	0.088	0.090	0.086
Mean	0.077	0.077	0.076	0.073