

Tools for Predicting Biomechanical Consequences of Alterations to Orofacial Anatomy

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ABSTRACT

We are extending our biomechanics simulation toolkit, ArtiSynth [Fels 2006], with new methods relevant to surgical planning. Our research directions are focused on upper-airway and cranio-facial anatomy and predicting functional deficits associated with jaw surgery, such as mandible reconstruction [Curtis et al. 1997]. The principle features of ArtiSynth include simulation of constrained rigid-bodies, fast finite-element methods for deformable bodies, contact between bodies, muscle models, and volume preservation. We are adding model editing capabilities and muscle activation optimization to facilitate progress on these research goals.

1. INTRODUCTION

Analyzing jaw biomechanics is difficult due to the inability to measure muscle and articulation forces directly. Advancements in dynamic computer simulation of biomechanics permit the analysis of the complex interplay of forces and motion in the oromandibular system [Koolstra and van Eijden 1997, Peck et al. 2000, Stavness et al. 2006]. The method has already been used to study unilateral chewing [Langenbach and Hannam 1999], and a recent model has included a dynamic hyolaryngeal component [Hannam et al. 2008].

We are developing ArtiSynth as a Java-based software platform for simulating the inframandibular (jaw, larynx, and tongue) biomechanics [Fels et al. 2006, Stavness et al. 2006]. Figure 1 shows some of the models in ArtiSynth. Our development is targeting simulation of altered anatomical structure and provides a graphical interface for interactive changes to musculoskeletal structure and properties. As such, ArtiSynth is ideal for simulating chewing in reconstructed mandibles.

It is hoped that detailed examination of the biomechanics of surgically reconstructed anatomy through computer simulation will provide pre-operative benefit in planning the reconstruction procedure and post-operative benefit by guiding rehabilitation to restore function. Simulation of a variety of potential reconstructions, e.g. different mandible grafts or tissue reattachments, may inform the patient-specific procedure to be performed and will complement other factors such as clinician experience and intuition. Given a model of a specific reconstruction, simulation of motor tasks with different muscle drive patterns may illuminate new motor strategies to effectively overcome the altered musculoskeletal structure. Knowledge of such strategies could potentially guide post-operative rehabilitation in order to retrain a patient to regain motor function.

In this paper we review the basic functionality of ArtiSynth and discuss in detail model editing and simulation control capabilities that are relevant for simulating motor tasks with altered

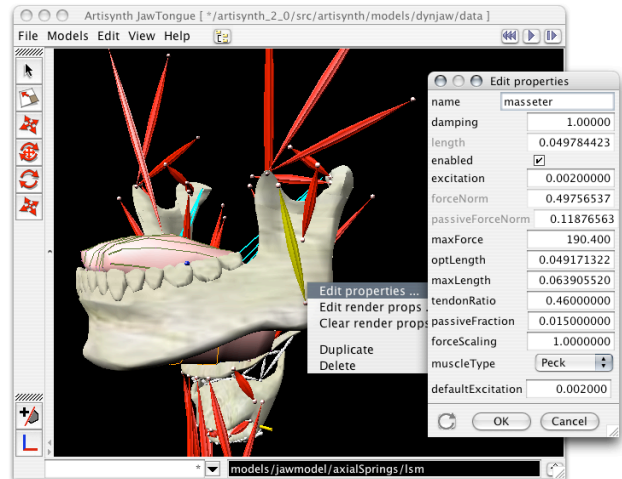


Figure 1 - Dynamic Jaw-Tongue-Hyoid model in ArtiSynth with left masseter muscle selected: showing pop-up edit menu and property editing panel for jaw muscle.

musculoskeletal structure. We also describe preliminary results of a simulated mandibular reconstruction.

2. ARTISYNTH SOFTWARE

We are developing an open-source software system for flexible simulation of musculoskeletal and soft tissue biomechanics. Our modeling efforts are directed to the anatomy of the upper airway. ArtiSynth supports the integration of different dynamic components such as rigid and deformable bodies, particles, springs, and muscle fibers, together with contact handling, rigid body constraints, and the ability to add customized components.

For the purpose of simulating surgical alterations and defects in the upper airway, several important functions are provided by ArtiSynth to facilitate model creation, integration and manipulation. For example, tight coupling between soft tissue models and rigid body dynamics is needed for understanding how changes in jaw structure will impact tongue movement. Likewise, easy-to-use interactive manipulation of muscle attachment and activation allows dynamic exploration of the impact of different muscle alterations will have on functional properties of the mouth. The main ArtiSynth features that are important for alteration modeling include:

Coupled Deformable and Rigid Body Dynamics

ArtiSynth has the capability to simulate the dynamics of mechanical systems composed of both rigid and deformable bodies, which allows for high fidelity models of musculoskeletal systems with rigid bones and soft tissue. Deformable body

dynamics are generally computed using finite element methods (FEM), with a choice of tetrahedral, hexahedral, or quadratic-tetrahedral elements. The constitutive equations are currently linear with small strain elasticity and stiffness-warping [Müller and Gross, 2004], although we anticipate adding nonlinear formulations suitable for tissue modeling. Incompressibility is implemented (for tetrahedral elements) using the projection technique of [Irving, et. al 2007]. Support is also provided for reduced coordinate models based on modal analysis. Rigid bodies can be coupled together using bilateral constraints to create systems of articulated bodies. Finite element models can be connected to rigid bodies by attaching individual nodes of the former to the latter.

Muscle Tissue

Muscle fibers are simulated in ArtiSynth as point-to-point actuators with interchangeable muscle models (e.g. non-linear Hill-type muscle dynamics). Fibers can be imbedded within a deformable body to simulate bulk muscle tissue, or attached to the surface of rigid bodies to simulate the principle force direction of large muscle groups. More complex muscle fiber types can be modeled in ArtiSynth as well.

Collision Detection and Handling

ArtiSynth also simulates contact between bodies with mesh-based collision detection. Rigid body contacts are resolved using velocity-based impulses computed using an LCP formulation similar to that described in [Lloyd 2005]. FEM contacts are handled by projecting interpenetrating nodes back to the contact surface, with care being taken to conserve momentum.

A primary focus of ArtiSynth is interactive simulation, with an emphasis on fast solution techniques and the ability to switch between high and low fidelity models as required. ArtiSynth also provides a number of numerical solvers and FEM techniques that span the range of simulation fidelity versus speed tradeoffs and provide flexibility to the user. ArtiSynth renders models graphically with OpenGL for visualization of simulations as well as for inspection and editing of models. Interactive modification a model's structure and dynamic properties are useful for simulating atypical situations, such as surgical reconstructions.

3. INTERACTIVE MODEL EDITING

ArtiSynth provides an extensible Application Programming Interface (API) that allows models to be built in Java code; however, we have also been developing Graphical User Interface (GUI) tools for building, editing, and saving models without requiring programming effort. These interactive tools permit a non-engineering user base, such as biologists and clinicians, who do not have the resources or willingness to build and edit models in Java code.

Interactive editing of model properties and structure can be used to easily make changes to a model based on planned surgical procedures in order to simulate the biomechanics of the resulting system. Any model component can be added, moved, and deleted from the model with a simple "click-and-drag" interface and all component properties can be modified. This direct manipulation approach enables model alterations such as moving muscle attachments, modifying finite-element model topology, and replacing rigid-body meshes. As a tool for analyzing the functional consequences of changes in an anatomical system, model editing capabilities are highly important.

Figure 1 illustrates how model components can be selected directly from the main graphical model view window. A right-click in the model view window brings up a pop-up context menu

with editing options. From this context menu a user can open sub-menus for editing dynamics properties, such as mass; or render properties, such as colour. The context menu includes other component specific editing functions such as duplicate, delete or add sub-components (e.g. add a marker to a rigid body component) to adjust the model complexity. Figure 1 illustrates a pop-up menu and property panel for the selected jaw muscle.

A selected component can also be geometrically transformed interactively. Transform widgets include translation, rotation, and scaling. Point translation can also be constrained to the surface of a mesh, which is useful for moving muscle attachment sites on the surface of a bone. Currently, only affine transformations are supported for rigid registration of model components. We are planning to include non-affine deformation fields for non-rigid registration of model components in ArtiSynth.

4. SIMULATION CONTROL AND OBSERVATION

Dynamic simulations of anatomy require a mechanism for inspecting the model outputs (such as position trajectories and contact forces) and modifying model inputs (such as muscle activation trajectories). We provide an interactive method for controlling and observing model simulation.

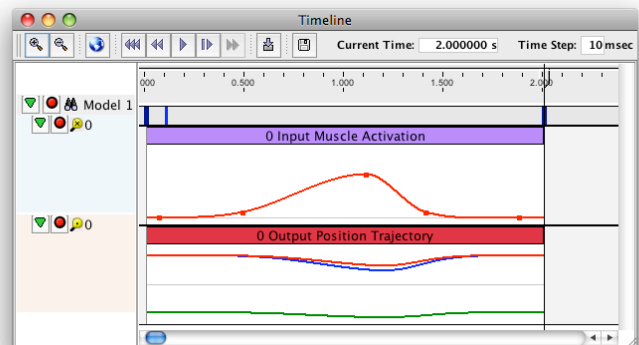


Figure 2 - Timeline interface with input muscle activation probe and output position trajectory probe.

Interactive Simulations: The Timeline Interface

Interactive simulation in ArtiSynth is supported using the Timeline user interface that allows editing and temporally arranging input and output data. The Timeline interface, shown in Figure 2, is based on a video editing metaphor with different input tracks being the control inputs for the model and other output tracks being the output. In ArtiSynth, these tracks are called probes. Users can then edit, move, group and view different probes. Input data can be manually edited with mouse-based interaction, which allows a human-in-the-loop simulation control. This type of simulation control has been successfully used to create a simulation of unilateral chewing with our jaw model [Hannam et al. 2008].

Manual manipulation of muscle drive patterns becomes difficult in multi-muscle anatomical systems to due a large redundant control space. Another direction for generating useful simulations toward predicting biomechanical result of anatomical changes is an automated or semi-automated simulation control system. We are developing optimization techniques to incorporate more automated muscle activation inputs.

Automated Simulations: Muscle Input Optimization

Automated techniques for generating plausible predictions of muscle drive patterns increase the utility of forward dynamics simulation and provide a mechanism to more easily and quickly evaluate the functional consequences of structural alterations to the model.

The inverse problem of computing muscle activation inputs to realize a desired motion output is ill-posed in anatomical systems due to kinematic and muscle actuation redundancy. In most anatomical systems, an infinite number of muscle activations can give rise to the same observed motion. Optimization techniques can be used to find a particular inverse solution that minimizes a predefined cost function over muscle activations.

Our initial development is focusing on quasi-static inverse solutions in which muscle activations are computed to achieve a sequence of desired quasi-static equilibrium poses. In this direction we plan to extend the work of Sifakis et al. [2005] for our simulation framework to determine the quasistatic inverse solutions. We are investigating different optimization techniques such as the Gauss-Newton method, trust region methods (Levenberg-Marquardt), and Interior Point methods [Boyd and Vandenberghe 2004; Wächter and Biegler 2006] for computing inverse solutions.

5. JAW RECONSTRUCTION SIMULATION

We are beginning a study, based on our published biomechanical simulations of human chewing [Hannam et al. 2008], that uses these new tools in ArtiSynth to examine prototypical cases of jaw motion deficits following surgical mandibular reconstruction [Curtis et al., 1996]. Resection of cancerous tissue in the mouth can include parts of the mandibular bone and adjacent jaw muscles. Typical reconstructions include a rigid graft to restore mechanical integrity of the mandible, however remaining muscle tissue may not be reattached to the graft site [Carlson and Marx, 1996, Hidalgo and Pusic, 2002, Mehta and Deschler 2004]. Post-reconstruction patients are known to have major problems chewing, however the consequences of missing jaw muscles in such reconstructions are not well-defined [Haraguchi et al., 2003]. Normally, jaw muscles activate bilaterally and asynchronously to create simultaneous, asymmetrical, compressive forces through the bite-points and temporomandibular joints. Their loss will predictably alter jaw motion and bite force. We will report our progress on jaw reconstruction simulation at the meeting.

6. SUMMARY

Simulation methods for surgical planning and rehabilitation continue to show promise. We have illustrated how some of the features of ArtiSynth provide the critical pieces for modeling jaw reconstructions. Some of the important features include: interactive model editing, control and observation, support for coupled, constrained rigid and deformable bodies, muscle modeling, collision handling, volumetric constraints. While our research directions are focused on upper-airway and cranio-facial anatomy and predicting functional deficits associated with jaw surgery, the ArtiSynth toolkit provides a general approach to modeling complex biomechanical systems. We continue to refine these tools and apply them to our jaw reconstruction studies.

ArtiSynth can be downloaded at www.artisynth.org.

7. REFERENCES

- Boyd, S. and Vandenberghe, L. Convex Optimization. Cambridge University Press. 2004.
- Carlson ER and Marx RE Mandibular reconstruction using cancellous cellular bone grafts J Oral Maxillofac Surg 54 889-897, 1996.
- Curtis DA Plesh O Miller AJ Curtis TA Sharma A Schweitzer R Hilsinger RL Schour L and Singer M A comparison of masticatory function in patients with or without reconstruction of the mandible Head Neck 19 287-296, 1997.
- Fels SS, F. Vogt, K. van den Doel, J.E. Lloyd, I. Stavness, and E. Vatikiotis-Bateson. ArtiSynth: A Biomechanical Simulation Platform for the Vocal Tract and Upper Airway. Technical Report No. TR-2006-10. Computer Science Dept., University of British Columbia. 2006.
- Hannam AG, I. Stavness, J.E. Lloyd, and S.S. Fels. A Dynamic Model of Jaw and Hyoid Biomechanics during Chewing. Journal of Biomechanics, In Press, 2008.
- Haraguchi M Mukohyama H Reisberg DJ and Taniguchi H Electromyographic activity of masticatory muscles and mandibular movement during function in marginal mandibulectomy patients J Med Dent Sci 50 257-264, 2003.
- Hidalgo DA and Pusic AL Free-flap mandibular reconstruction : a 10-year follow-up study Plast Reconstr Surg 110 438-449, 2002.
- Irving, G., Teran, J., and Fedkiw, R., Volume Conserving Finite Element Simulations of Deformable Models. Proceeding of ACM SIGGRAPH, 2007.
- Koolstra, J.H., van Eijden, T.M., The jaw open-close movements predicted by biomechanical modeling. Journal of Biomechanics 30, 943-950, 1997.
- Langenbach, G.E.J., Hannam, A.G., The role of passive muscle tensions in a three-dimensional dynamic model of the human jaw. Archives of Oral Biology 44, 557-573, 1999.
- Lloyd, J. E., Fast Implementation of Lemke's Algorithm for Rigid Body Contact Simulation. Proceedings of IEEE Conference on Robotics and Animation, 4549-4554, 2007.
- Müller, M., and Gross, M., Interactive Virtual Materials. Proceedings of Graphics Interface, May 17-19, 239-246, 2004.
- Peck, C.C., Langenbach, G.E.J., Hannam, A.G., Dynamic simulation of muscle and articular properties during human wide jaw opening. Archives of Oral Biology 45, 963-982, 2000.
- Sifakis, E., Neverov, I., and Fedkiw, R., Automatic determination of facial muscle activations from sparse motion capture marker data. ACM Trans. Graph., 24(3):417-425, 2005.
- Wächter, A. and Biegler, L.T. On the Implementation of a Primal-Dual Interior Point Filter Line Search Algorithm for Large-Scale Nonlinear Programming, Mathematical Programming 106(1), pp. 25-57, 2006