Towards Predicting Biomechanical Consequences of Jaw Reconstruction

Ian Stavness, Alan G. Hannam, John E. Lloyd, and Sidney Fels

***Abstract*— We are developing dynamic computer models of surgical jaw reconstructions in order to determine the effect of altered musculoskeletal structure on the biomechanics of mastication. We aim to predict post-reconstruction deficits in jaw motion and force production. To support these research goals we have extended our biomechanics simulation toolkit, ArtiSynth [1], with new methods relevant to surgical planning. The principle features of ArtiSynth include simulation of constrained rigid-bodies, volume-preserving finite-element methods for deformable bodies, contact between bodies, and muscle models. We are adding model editing capabilities and muscle activation optimization to facilitate progress on post-surgical simulation. Our software and research directions are focused on upper-airway and cranio-facial anatomy, however the toolset and methodology are applicable to other musculoskeletal systems.**

I. INTRODUCTION

Cancer of the oral cavity can invade the mandible and nearby muscles. Treatment usually involves resection of the cancerous tissue and may include large sections of the mandible as well as tongue and jaw muscles. Reconstruction of the affected area varies and usually includes a mandibular graft to restore aesthetics and function. The procedure results in a dramatic alteration of orofacial anatomy and even with reconstruction, the loss of bone mass and musculature can produce functional deficits in mastication, speech, tongue mobility, jaw mobility, and bite force generation [2] [3].

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 [4] [5] [6]. The method has already been used to study unilateral chewing [7], and a recent model has included a dynamic hyolaryngeal component [8].

In the present study, we are using our Java-based software platform, ArtiSynth, for simulating inframandibular (jaw, larynx, and tongue) biomechanics [1] [6]. Figure 1 shows our dynamic inframandibular model. ArtiSynth provides a graphical interface for interactive changes to musculoskeletal structure and properties. As such, it is ideal for simulating chewing in reconstructed mandibles.

We believe that in the near future, detailed examination of the biomechanics of surgically reconstructed anatomy through computer simulation will provide pre-operative benefit in planning reconstruction procedures and post-operative benefit by guiding rehabilitation. Simulating a variety of potential reconstructions, e.g. different mandible grafts or tissue reattachments, may inform the patient-specific procedure to be performed, and 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 compensate for the altered musculoskeletal structure. Knowledge of such motor strategies could potentially guide post-operative rehabilitation in order to retrain patients regaining motor function.

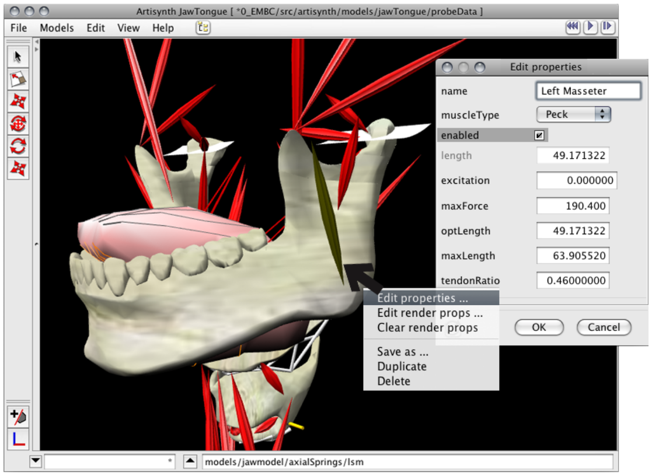

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Fig. 1. Dynamic Jaw-Tongue-Hyoid model in ArtiSynth. A property editing panel is shown for the selected muscle

In this paper, we present preliminary results of simulating chewing deficits associated with mandibular reconstruction by means of our biomechanical modeling toolkit.

II. THE BIOMECHANICS TOOLKIT; ARTISYNTH

Our approach was to use our existing jaw model and chewing simulation developed in ArtiSynth and to modify it using ArtiSynth's model editing tools to be consistent with the typical outcomes of jaw reconstruction surgery. We performed simulations with the new jaw-reconstruction model using nominal muscle drive patterns for chewing and observed the resulting motion and force production deficits. Here we discuss the tools in ArtiSynth that we used for model creation, modification and simulation.

I. Stavness, J. Lloyd, and S. Fels are with the Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, Canada `stavness@ece.ubc.ca`, `lloyd@cs.ubc.ca`, `ssfels@ece.ubc.ca`

A. G. Hannam is with Department of Oral Health Sciences, Faculty of Dentistry, The University of British Columbia, Vancouver, Canada `ahannam@interchange.ubc.ca`

A. ArtiSynth Simulation Platform

ArtiSynth provides an extensive toolset to facilitate model creation, integration and manipulation for the purpose of simulating surgical alterations and defects in the upper airway. A primary focus of ArtiSynth is interactive simulation, with an emphasis on fast solution techniques that are sufficiently accurate for biomechanical analysis. ArtiSynth renders models graphically with OpenGL for visualization of simulations as well as for inspection and editing of models. Interactive modification of a model's structure and dynamic properties are useful for simulating atypical situations, such as surgical reconstructions.

1) Coupled Deformable and Rigid Body Dynamics: ArtiSynth has the capability to simulate the dynamics of mechanical systems composed of both rigid bones and deformable 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 [9], although the addition of nonlinear formulations suitable for tissue modeling is anticipated. Incompressibility is implemented for FEM models using the projection technique of [10]. 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.

2) 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 [11]. FEM contacts are handled by projecting interpenetrating nodes back to the contact surface, with care being taken to conserve momentum.

3) 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.

B. Simulation Control and Observation

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

1) The Timeline Interface for Interactive Control: Interactive simulation in ArtiSynth is supported using the Timeline user interface that allows editing and temporally arranging input and output data. The Timeline interface 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 [8].

2) Optimization for Automated Control: Manual manipulation of muscle drive patterns becomes difficult in multi-muscle anatomical systems to due a large redundant control space. Inverse modeling would permit automated or semi-automated simulation control. Following the work of Sifakis et al. [12], our initial development has focused on quasi-static inverse solutions in which muscle activations are computed to achieve a sequence of desired quasi-static equilibrium poses. Quasi-static poses are relevant for simulating sequences of speech articulation poses and relatively slow movements, such as chewing, where the inertia effects are minimal.

The inverse problem can be posed as an non-linear optimization problem that selects muscle activations to match the desired kinematic state of the mechanical system, while also satisfying specified constraints, such as minimizing muscle energy, achieving a desired system stiffness, or enforcing muscle groupings. ArtiSynth includes facilities to compute the force Jacobians for the mechanical system, which permits the use of gradient-based methods for non-linear programming, such as the Gauss-Newton, trust-region (Levenburg-Marquardt) [13], and interior point methods [14]. We are continuing to refine the optimization techniques and incorporate rigid body constraints in the inverse solution. We strive for a flexible tool that provides automatically computed muscle activations along with controls to refine the solution to match a user's expectations and *a priori* knowledge.

C. Interactive Model Editing

Interactive editing of model properties and structure can be used to easily make changes to a model based on planned surgical procedures. In ArtiSynth, 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 either the main graphical model view window or from a hierarchical list of named model components. 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.

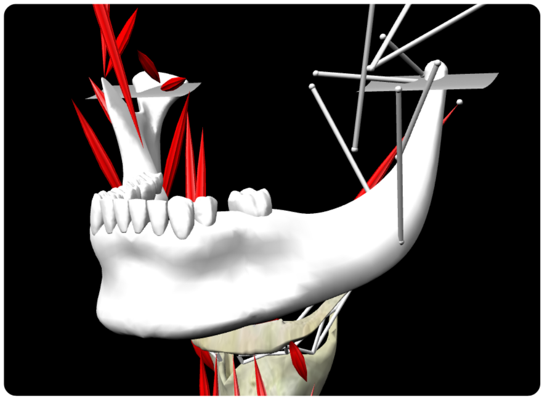

Fig. 2. Oblique view of jaw reconstruction model: left side graft with white lines denoting missing muscle groups

III. JAW RECONSTRUCTION SIMULATION

Our study is based on our published dynamic simulations of human chewing [8] and has used the new tools in ArtiSynth to examine jaw motion deficits following surgical mandibular reconstruction. 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 functioning muscle tissue may not be reattached to the graft site [3] [15]. Post-reconstruction patients can have major problems chewing [2], however the consequences of missing jaw muscles in such reconstructions are not well-defined [16]. 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.

A. Jaw-Hyoid Model

Our existing dynamic jaw-hyoid model has been described in detail elsewhere (see [6]). The model consists of rigid bodies for maxilla, mandible, hyoid, thyroid, and cricoid, forty Hill-type muscle actuators, along with curvilinear articular guidance at the joint and rigid contact at the teeth. Muscle drive patterns have been created to simulate typical unilateral chewing with the model (see [8]). A dynamic FEM tongue can be attached to the jaw-hyoid for a more complete inframandibular model, however at this time the chewing simulations are preformed with the jaw-hyoid model alone.

Our post-reconstruction model assumes that the jaw resection required a graft from the premolar teeth on the left side to the left joint. Figure 2 shows the graft and missing muscles. The original condylar and coronoid processes are lost, but a new condylar process has been included in the graft that provides compressive resistance at the left joint. The affected side therefore has a number of missing muscles (shown in Figure 2), including:

1) left-side closers (anterior, middle and posterior temporalis, deep and superficial masseter, medial pterygoid)
2) left-side forward translators (lateral pterygoids)
3) left-side floor-of-mouth muscle (mylohyoid)

Vertical passive resistance is included in the model to represent scar tissue that forms a bed around the graft site. The passive viscoelastic properties of the reconstruction site are not well known and may vary considerably with the amount of tissue that is reattached to the graft site during surgery.

B. Post-Reconstruction Chewing Simulation

We aim to assess effects of jaw reconstruction alterations on jaw motion, bolus and articular forces during chewing attempted with normal activation profiles for the remaining muscles. We assume that initially a post-reconstruction patient would attempt to chew using a previously-familiar pattern of muscle use, and therefore would demonstrate biomechanical deficiencies in jaw motion trajectories and bolus compression.

Patients predominantly chew on the intact side because of sensation deficits on the reconstructed side. Thus, we have simulated right side chewing with the left-side reconstruction. The food bolus in the simulation is 10mm thick, and needs 30N to crush. The chewing cycle duration for the normal jaw model is 732ms [8].

C. Preliminary Results

The simulation results reveal a significant alteration of jaw motion during attempted chewing. Figure 3A shows a trace of the frontal plane incisor-point chewing envelope for normal and reconstruction models. The unilateral loss of the lateral pterygoid and mylohyoid muscles causes jaw deviation to the ipsilateral side during opening with protrusion. The skewed opening trajectory is shown in Figure 3B and is due to lateral pterygoid activity on the unaffected side. Also, during the closing chew stroke the absence of left jaw-closing muscles causes rotation of the jaw in the frontal plane when the food bolus is compressed between the molar teeth. Non-compressive forces develop on the affected joint, which causes disarticulation (shown in Figure 3C). The loss of affected side muscles also prevents sufficient bite force to crush the simulated food bolus.

Our initial simulations are best viewed as a demonstration of the tools in ArtiSynth for modeling the consequences of jaw reconstruction. It does not necessarily represent an actual case as validation studies are in progress.

IV. FUTURE DIRECTIONS

Our chewing simulations currently do not include the tongue. We have developed a FEM tongue model [17] that can be integrated with the dynamic jaw and laryngeal components. A complete jaw-tongue-hyoid model will enable us to examine how changes in jaw structure will impact tongue movement in future studies.

We also plan to perform future mastication simulations using the optimization-based muscle drive prediction techniques that we are developing. Plausible predictions of

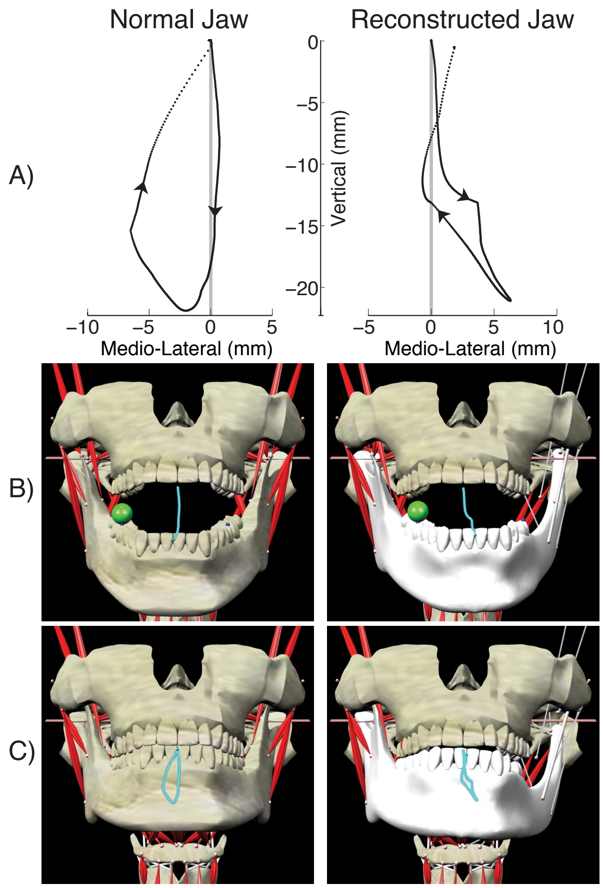

Fig. 3. Unilateral chewing simulation results for normal jaw (left) and reconstructed jaw (right): A) plot of incisor point motion in the frontal plane (x-axis is medio-lateral displacement, y-axis is vertical displacement); B) opening deviation to reconstruction model's left side; C) left joint separation during bolus compression for reconstruction model.

muscle drive patterns will allow us to more easily and quickly evaluate the functional consequences of structural alterations to the model in motor tasks such as mastication and speech. We also plan to explore how patients might adapt and compensate for their muscle deficiency. Knowledge of effective muscle patterns in the model could inform rehabilitation strategies for patients with similar loss of reconstruction-side muscles. Using the model editing facilities in ArtiSynth we also plan to explore alternative reconstruction models, e.g. reattaching selected muscles to the graft site. Such simulations could determine mechanical means to mitigate the observed chewing deficits.

V. 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 rigid and deformable bodies, muscle modeling and collision handling. Using interactive model editing tools in ArtiSynth we have created a reconstructed mandible model. Dynamic simulations of chewing with nominal muscle drive patterns illustrate deficits in jaw motion and force production. Further validation studies are planned along with simulations of potential corrective strategies. While our research directions are focused on upper-airway and craniofacial 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 validate our jaw reconstruction studies.

ArtiSynth can be downloaded at www.artisynth.org.

VI. ACKNOWLEDGMENTS

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