Dynamic Modeling of Human Jaw and Laryngeal Biomechanics

by

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Abstract

Computational modeling is an important tool for studying the structure and function of human anatomy in biomedicine. In this thesis, a dynamic, anatomically accurate model of the human mandibular and laryngeal structures is presented. The complexities of the infra-mandibular anatomy are discussed along with previous approaches to jaw modeling and a detailed description of dynamic modeling techniques. Forward dynamic simulations, created with the model's comprehensive user-interface, are reported that show consistency with previously published jaw modeling literature. Laryngeal motion during swallowing was simulated and shows plausible upward displacement consistent with published recordings. Simulation of unilateral chewing was also performed with the model to study mastication mechanics. A novel open-source modeling platform, ArtiSynth, is described in the context of its use and extension in the construction and simulation of the biomechanical jaw and laryngeal model.

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Chapter 1

Introduction

A fundamental avenue of scientific investigation has been the attempt to describe and explain the physical mechanics of the human body. Recent advancements in this field have adopted mathematical models and numerical computation to capture the physical phenomena associated with human biomechanical function. This thesis describes the development of a computational dynamic modeling tool for analyzing the biomechanics of the human jaw and laryngeal system.



Figure 1.1: Our jaw model showing viewer, control panel, and timeline.

Chapter 1. Introduction

The human jaw and larynx, together with the tongue, form the inframandibular system and are the active anatomical players in speech production, mastication, and swallowing. The system is also critical in respiration, as illustrated by the respiratory disorder Obstructive Sleep Apnea, which is caused by dysfunction of infra-mandibular anatomy. The system is composed of a complex arrangement of anatomy including a large number of jaw, tongue, and neck muscles, complex soft tissue of the oral cavity and larynx, and multiple points of skeletal articulation.

We have constructed a high fidelity, dynamic, physics-based computer model of the human jaw and laryngeal complex utilizing high resolution CT data for creating the model geometry and fast computational techniques for realtime simulation. It is the most complete model of integrated craniomandibular anatomy created to date, incorporating the cranium, mandible, hyoid bone, cricothyroid complex, and associated muscles, which enables analysis of the interactions between the jaw and laryngeal systems in a range of physiological tasks.

Our model has been created using ArtiSynth [17], an open-source biomechanical modeling system that we have developed specifically for dynamic modeling of the human upper airway. Our jaw modeling efforts have both utilized and extended the ArtiSynth software infrastructure. Using ArtiSynth, we have created a graphical user interface allowing non-computer specialist researchers to perform advanced simulations of jaw and laryngeal motion. The complete jaw model and simulation interface is pictured in Figure 1.1. We have employed an expert dental researcher to use the toolset for analyzing jaw mechanics and have gathered feedback to refine the simulation-interface.

 $\mathbf{2}$

As validation, we used published records of muscle drive to create jaw motion simulations for a range of functional tasks demonstrating plausible ranges of jaw motion (rest posture, forward protrusion, and mid-line opening) as well as the human feeding motions of swallowing and mastication. Our jaw modeling toolset has been used to create a definitive simulation of mastication that is consistent with published recordings of incisor-point and condyle motion. Continued research efforts are focused on the analysis of mastication mechanics and the incorporation of a dynamic tongue into our system to create a fully integrated infra-mandibular model.

1.1 Motivation

The research presented in this thesis was motivated by the desire to better understand the biomechanics of the integrated jaw and larynx anatomical system. In this section we discuss the utility of dynamic computational modeling in general and with respect to anatomical systems. The importance of modeling integrated anatomical systems and developing researcher-friendly simulation-interfaces is also significant as motivation for the basic directions of our modeling efforts.

Computer Modeling

Modeling is a tool that complements direct experimental research. Modeling establishes a mathematical representation of a system and can incorporate measured experimental data and simulate observable outputs [2]. The model's utility is based on its ability to make output predictions for arbitrary changes in its internal parameters and inputs. A model can also make predictions of parameters of the system that cannot be measured. This is particularly important for experimentation that involves measurement that will disturb or destroy the system under observation.

Anatomical Modeling

In studying human anatomy, computational modeling is an important tool for analyzing the relationship between structure and function in physiological actions. A biomechanical system can be decomposed into a set of interconnected mechanical structures, which have mathematical representation. This decomposition can be performed to varying levels of fidelity, resulting in models that capture different levels of representation of the system. Epstein and Herzog [16] provide a discussion of representation and fidelity in the context of modeling skeletal muscles.

Anatomical modeling is particularly valuable for studying medical disorders. Models that are validated by simulating normal human function can be modified systematically to simulate dysfuntions of those tasks. The simulation of medical disorders can be used to analyze both the causes of dysfunction and explore possible corrective procedures. The biomedical applications of cranio-mandibular modeling are significant and include the analysis of morphological and functional pathology, surgical planning and prediction, and the role of jaw posture during obstructive sleep apnea.

Integrated Anatomical Subsystems

Modeling interconnected anatomical subsystems is important for studying interactions between those structures and for extending the range of functional tasks that one model can simulate. For jaw modeling, the addition of dynamic laryngeal anatomy can be used to study interaction forces that develop in the sub-mandibular muscles during jaw motion. Interaction forces applied by the laryngeal structure on the mandible have an important impact on free jaw motion in speech. Hyoid motion occurs during most jaw function and has been shown to be important in wide jaw opening [52]. Modeling the laryngeal subsystem allows for simulation of other classes of physiological action including swallowing sequences [18], vocal chord stretching [74], and effort-closure of the larynx [18].

Simulation User-Interface

A comprehensive simulation environment and interface vastly extends the utility of computational modeling. Typically anatomical specialists who could best utilize computer modeling are not computer specialists and thus are not able to engage in computer programming. The requirements for a comprehensive simulation environment include: control of input data and simulation progression, display of salient output, and a reliable method to save simulation data. Beneficial features of such an interface include: a graphical user interface (which requires no programming), fast process to tune simulations, and adaptability so that the interface can be tailored to a specific user and simulation situation. For this reason, we have focused much of our effort on creating a usable, complete simulation environment for jaw experts to study jaw mechanics.

1.2 Overview of Contributions

The contributions of this thesis can be classified into novel aspects of the model, advancements made in development of the simulation interface, and results of simulations performed with the system. The chapters of this thesis are organized based on divisions of the contributions presented here.

1.2.1 Model

Our dynamic jaw and laryngeal model has advanced the state-of-the-art in jaw modeling in four main ways:

- Sub-Mandibular Anatomy. The addition of laryngeal anatomy in our model is a significant advancement that provides a more comprehensive, holistic approximation of the human jaw system.
- Constrained TMJ. We have created a unique model of the temporomandibular joint (TMJ) utilizing hard rigid-body constraints that provide realistic reaction forces. Our TMJ is based on a typical semi-adjustable dental articulator device and has lateral and posterior guidance that approximates the 3D structure of the articular fossa.
- Modular Design. Our model is composed of modular subcomponents that can be easily interchanged with more rudimentary or more complex models. Modularity makes our model more extensible and modifiable for future studies.
- Amira Data Support. We have developed support software for importing registered mesh geometry and landmark data from a widely

used medical data visualization tool Amira into a dynamic model in ArtiSynth. Our data integration infrastructure allows for further incorporation of subject-specific data into our model as required.

1.2.2 Interface

The simulation-interface development for the jaw model is an important contribution establishing the system as a usable tool for non-computer specialist researchers.

- Integrated Controls. We have integrated input data manipulation, simulation time control, and output data visualization into one graphical user interface. Integrated control creates intuitive and fast interface for creating and refining forward simulations of jaw motion.
- Changeable Model Parameters. We have developed a set of control panels that expose internal model parameters to the user for modification. This creates a flexible tool for testing biomechanical hypotheses and analyzing dysfunction through systematic changes in model properties.
- User-centered Refinement. We have used feedback from an expert user to refine our interface design. The process of interface refinement has contributed to the ArtiSynth project through testing with a real user and by motivating core interface extensions such as the development of functional data probes.

1.2.3 Simulation

Simulations performed with our jaw modeling toolset have generated results that contribute to jaw biomechanics research.

- Laryngeal Motion. Our simulation results illustrate the effect of laryngeal depression on wide jaw opening. We have also successfully simulated plausible forward and upward laryngeal displacement during swallowing.
- Mastication Research. We have created a comprehensive study of modeling the human mastication cycle. Our simulation results demonstrate incisor position envelopes and reciprocal condylar motion during chewing that is consistent with six degree-of-freedom motion records.
- Validation Approach. We have described and explained the utility of modeling with mixed subject-specific and average-valued data as well as illustrating model validation through simulating multiple functional tasks with constant model parameters.

1.3 Thesis Organization

The following chapter provides an overview of related work, including background information on the relevant functional anatomy, a discussion of previous jaw modeling approaches, and details regarding dynamic computational modeling, which is the basis for our jaw and laryngeal model. The body of this thesis, Chapters 3 - 5, are organized based on the contribution divisions given above. Chapter 3 discusses the technical components of our jaw model, Chapter 4 the simulation interface, and Chapter 5 the results of our validation simulations. The final chapter presents avenues for future research using and extending the model along with concluding remarks. The appendices report dynamic properties and data sources for our model as well as mathematical details on numerical integration.

Chapter 2

The Jaw and Laryngeal System

In this thesis we employ dynamic modeling techniques to simulate the function of the integrated jaw and larynx. Dynamic modeling requires physicsbased mechanical representations of anatomical components that are arranged and connected in the same manner as the physical system. As such, a dynamic model incorporates *a priori* knowledge rooted in the physical anatomical system in an attempt to recreate its behaviour. For this reason information regarding anatomical structure and physiological function is of great importance for our efforts. We begin this chapter with a discussion of relevant functional anatomy: specifically, we detail its complexity and influence on our modeling approximations.

After presenting background anatomical information our focus will shift to previously published approaches to modeling the human jaw system. The earliest attempts at representing the jaw system were mechanical devices. We discuss robotic systems as they are capable of recreating physical dynamics and a passive apparatus, the dental articulator, due to its significance in clinical dentistry. More recent jaw modeling attempts use numerical computation as a substitute for complex mechanical structures. Computation models have the added advantage of being infinitely modifiable and adaptable to specific subjects or medical conditions. We will contrast kinematic computational

models that merely represent jaw motion with dynamic computational models that are capable of relating physical properties, forces, and motion during dynamic jaw functional tasks.

After having made our case for the advantages of dynamic modeling we will delve into the details of the technique in the final section of the chapter. We start with a discussion of the mathematical underpinnings of dynamic physics-based modeling including numerical integration methods required to solve for the dynamic equations of motion. We will then discuss previous approaches to modeling the jaw's anatomical sub-components including softtissues, muscles, and the temporomandibular joint. The anatomical component models rely heavily on anatomical data to provide geometric and dynamic properties representative of human anatomy. We will examine the types of data that are available to inform dynamic modeling and the specific published datasets that are relevant to our jaw and laryngeal model's anatomical properties and functional simulations.

2.1 Functional Anatomy

The human infra-mandibular region is a complex anatomical system involved in the primary human functions of feeding, breathing, and communicating. It is composed of intricately detailed skeletal features, over forty individual muscle groups, soft-tissues of the tongue and larynx, and a unique compound joint containing a deformable disc - all which work in concert to enable fast six degree-of-freedom jaw movements and large three dimensional bite forces. Figure 2.1 provides an overview diagram of the infra-mandibular anatomy.

In this thesis we present the use of dynamic modeling techniques to generate an approximation of the jaw and laryngeal anatomy in order to represent the mechanics of the system. The model is constructed by building up subcomponents that mimic each individual anatomical entity in the physical system. Therefore the complexities of the anatomical subcomponents and overall system are important for informing our modeling decisions.

In this section we describe the principle pieces of the infra-mandibular anatomical puzzle and how those pieces fit together to create function. We first describe the skeletal components, starting with the dentition and moving outward to describe the head and laryngeal structures. We will draw attention to the important tissues and ligaments that connect the skeletal structure, and describe in detail the primary point of jaw articulation: the temporomandibular joint. We also describe the musculature of the head, jaw, and neck because muscles are the active components involved in generating skeletal motion. Finally, we briefly discuss the functional significance of the tongue and facial tissues connected to the jaw and hyoid.

The anatomical information provided in this section has been compiled

from Okeson [53], Last [41], and van Eijden et al. [78].



Figure 2.1: An overview of the infra-mandibular anatomy showing principle skeletal structures and muscle groups.

2.1.1 Skeleton

In this section we describe the bony skeleton of the head: teeth, maxilla, mandible, cranium, and hyoid bone, as well as the cartilaginous structures of the larynx: thyroid, cricoid, arytenoids, and epiglottis. These structures have varying levels of rigidity with thick, dense bone being most stiff and thin cartilage being most deformable. Our modeling purposes are aimed at representing the gross dynamic motion of these structures, as opposed to their internal deformation; therefore, we currently model all of the skeletal structure (bone and cartilage) as being purely rigid, which greatly simplifies our modeling efforts.

Teeth

The human dentition consists of an upper and lower arch each containing sixteen teeth. The tooth body is divided into an exposed crown and an internal root that anchors it to the bone. The tooth root sits within bony sockets called alveolar processes in the mandible and maxilla and are attached by the periodontal ligament, as shown in Figure 2.2. The periodontal support fibres provide force distribution and shock absorption for the teeth, as well as sensitive nerve endings to detect tooth loads. The upper dental arch is slightly wider and longer than its lower counterpart in order for tooth crowns to fit together during intercuspation.

In our model we represent the upper and lower dentitions as a set of individual tooth crowns rigidly fused to the maxilla and mandible. Additionally, contact between the teeth during intercuspation is approximated as contact between flat surfaces as discussed in section 3.3.2.

Maxilla

The maxilla bone forms the upper jaw and is fused with the surrounding bony structure of the cranium. The maxilla extends from the floor of the nasal cavity and lower border of the orbit to the hard palate and alveolar process of the upper dental arch (see Figure 2.3).



Figure 2.2: A tooth seated within the bony alveolar process and connected by the periodontal ligament [53] (© Elsevier, 2003, adapted with permission).

Mandible

The mandible, pictured in Figure 2.4, is a u-shaped bone connected to the skull through muscles, ligaments, and contact at the TMJ. The frontal arch-shaped portion of the bone forms the alveolar process for the lower teeth. The posterior portion of the mandible extends upward into the ascending ramus which forms two processes. The anterior coronoid process flattens medio-laterally and serves as the insertion site for the temporalis muscle, extending the mechanical advantage of this muscle for generating closing torque on the jaw. The posterior process of the ascending ramus, which has a convex shape, is termed the "condyle" and articulates with the cranium at the TMJ.

The shape of the condyle has been approximated as a ellipsoid in previous dynamic jaw models (see section 2.2.3). We maintain the complex shape of



Chapter 2. The Jaw and Laryngeal System

Figure 2.3: The maxilla bone, known as the "upper jaw", showing the upper dental arch, lower orbit, and zygomatic arch [24].

the condyle in our mandible structure (see section 3.3.1), which is potentially important for studying force distribution at the temporomandibular joint.

Cranium

The cranium is the bony structure of the upper head that encloses the brain. The base on the cranium forms the temporal bone, which serves as the articular surface for the mandibular condyle. The posterior area of the temporal bone is concave and forms the articular fossa (colloquially referred to as the "jaw joint socket" due to its concave shape). Anterior to the fossa is the articular eminence, a convex bony process that is the pathway for the condyle during jaw opening and protrusion (see Figure 2.6). The articular eminence





Figure 2.4: The mandible bone, known as the "lower jaw", showing the lower dental arch and the ascending ramus forming the coronoid process and condyle.

is designed to sustain large joint loads as it consists of thick, dense bone.

We model the complex shapes of the temporal bone including the articular eminence and fossa (see section 3.3.1); however, the temporomandibular joint is currently approximated as a planar contact surface in our model as discussed in section 3.3.3. The upper lateral portions of the cranium are also included in our model as attachment sites for the temporalis muscle groups, but the frontal portion of the skull, including with the orbits, is omitted as it has little significance to jaw function.

Hyoid

The hyoid bone is a floating, u-shaped bone that is connected below the mandible by the suprahyoid muscles. It sits along the upper border of the thyroid cartilage connected with the hyothyroid membrane as shown in Figure 2.5. The hyoid serves as an anchor for the posterior muscle fibres of the tongue.

Larynx

The larvnx is a deformable organ composed of a chain of cartilaginous structures enclosed by connective tissue, ligaments, and muscles. The cricoid forms a ring of cartilage that serves as the base of the laryngeal complex connecting to the first ring of the trachea. The cricoid is narrow at its anterior ridge and broadens on the posterior side of the ring, termed the cricoid lamina. The two bilateral arytenoids have a pyramidal shape and articulate with the upper border of the cricoid lamina. The arytenoids serve as an attachment point for the vocal cords and both translate and rotate to open, close, and stretch the vocal cords. The thyroid, a large v-shaped cartilage, is open to the back and forms a pointed junction anteriorly, which is termed the "Adam's apple." The thyroid articulates with the cricoid by hinging about a transverse axis intersecting the two inferior processes of the thyroid, which causes stretching of the vocal cords. The epiglottis is a passive flap of cartilage that rests along the interior surface of the thyroid and hyoid and functions in swallowing to block off the airway by folding over the top of the cricoid.

Although the cartilaginous bodies of the larynx described above are de-

formable, we approximate the structures as rigid to reduce the computational complexity of our model. The deformation of the larynx in our model is solely achieved through the soft connective tissue as discussed in section 3.3.5.



Figure 2.5: The anatomy of the human larynx showing cartilage structures and connective tissue [24].

Larynx Connective Tissue. The laryngeal cartilage structures are slung below the hyoid bone by the hyothyroid membrane and ligament. Internally they are linked by the cricothyroid ligament, cricoarytenoid ligaments, and other connective tissue. The lower border of the cricoid is connected to the first ring of the trachea by the cricotracheal ligament which resembles the connective tissue that links the rings of the trachea.

Vertebrae

The vertebrae are the ringed bones that enclose and protect the spinal cord. They extending in a chain from the base of the cranium to the pelvis. The upper section, named the cervical vertebrae (C1 - C7), form the skeleton of the neck and provide support to skull. Functionally, each vertebra articulates in sequence to enable movement of the head. The vertebrae also provide convenient anatomical landmarks as their dense structure is easily visible in medical images (see Figure 2.10).

In our model we approximate the vertebrae as a single fixed rigid structure (see section 3.3.1). The vertebrae geometry serves as a landmark for registration of other skeletal components, particularly the floating structures of the larynx.

2.1.2 Temporomandibular Joint

The TMJ is one of the most complex joints in the body and is classified as a compound joint, due to the interaction of the mandibular condyle, temporal bone, and non-ossified TMJ disc as shown in Figure 2.6. The TMJ allows for a complex function of combined hinging and translation of the mandible. The TMJ is formed by the articular fossa and eminence of the temporal bone and the condyle of the mandible bone separated by the articular disc. The disc is composed of fibrous connective tissue and is most dense anteriorly and medially, where the largest joint loads are induced. The disc is held in place by a series of ligaments connected to the articular and condylar bone.

The surfaces of the condyle, articular eminence, and disc are smooth

and the joint cavities lining the surfaces produce synovial fluid, all which aid in reducing friction during joint motion. The disc deforms to fit the irregular contact surfaces in order to distribute forces effectively; however, the morphology of the disc is not irreversibly changed during normal function. Destructive forces or structural joint changes can irreversibly change disc morphology, which produces biomechanical changes that may lead to joint dysfunction.



Figure 2.6: Cross sectional view of the temporomandibular joint showing: (a) the condyle and articular disc, (b) surrounding connective tissue and muscles [53] (© Elsevier, 2003, adapted with permission).

In our model we approximate the TMJ as a rigid contact surface as described in section 3.3.3. Models designed specifically for analyzing TMJ dynamics have included deformable structure for the articular disc and are discussed in section 2.3.4.

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TMJ Ligaments. The capsular ligament surrounds and encloses the entire TMJ attaching from the temporal bone to the neck of the condyle. The oblique portion of the temporomandibular ligament extends from the zygomatic process on the maxilla to the lateral surface of the condylar neck. Both inextensible ligaments function to restrict lateral, posterior, and inferior motion on the condyle and prevent joint dislocation. Previous modeling and imaging studies have reported that the TMJ remains in compression in all jaw function, without ligament tension due to the mechanical structure and passive forces in the closer muscles [39].

2.1.3 Musculature

The mandibular muscles produce forces that move the jaw and cause tooth forces during chewing and clenching. The submandibular muscles are capable of opening the jaw and lifting the laryngeal complex during swallowing. The jaw musculature also stabilizes the system and prevents extreme jaw displacement through passive tension generated by muscle stretch. The muscles of the infra-mandibular system can be coarsely grouped into "jaw closers", "jaw openers", and "infrahyoid" muscles as shown in Figure 2.7.

Although the mandibular muscles have volume, they generally do not significantly bend between their origin and insertion sites (with the exception of the superior lateral pterygoid and omohyoid muscle groups). For this reason they are good candidates for being represented with straight-line muscle models. A review of previously published muscle modeling techniques is presented in section 2.3.3, while a description of the muscles included in our jaw model is provided in section 3.3.4.



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Figure 2.7: The principle muscle groups of the human head and neck [53] (© Elsevier, 2003, adapted with permission).

Jaw Closer Muscles

Jaw closing muscles include the masseter, temporalis, and medial pterygoid muscle groups as shown in Figure 2.8. Each muscle group has large attachment areas and can be further subdivided based on muscle fibre direction [25].

The masseter is typically divided into superficial and deep parts; however, the muscle is further compartmentalized into layers of muscle sheets with different fibre angles. Both masseter groups originate along the length of the zygomatic arch. The superficial fibres insert into the lower portion of the ramus with a forward angle, while the deep fibres run mostly vertical, inserting into the upper two-thirds of the ramus. The fan-shaped temporalis muscle originates from a large area on the lateral side of the skull and inserts in the coronoid process and the inner side of the ramus. The temporalis

fibres run between the zygomatic arch and the skull. The muscle is typically grouped into anterior fibres that are directed vertically and posterior fibres that are angled backward. The medial pterygoid muscle is a thick, heavily pennated muscle group originating from the pterygoid fossa and inserting into the inner side of the lower part of the ramus.



Figure 2.8: Jaw closing muscle groups: masseter, temporalis, and medial pterygoid [53] (© Elsevier, 2003, adapted with permission).

Jaw Opener Muscles

The jaw opening muscles include the lateral pterygoid, digastric, mylohyoid, and geniohyoid muscle groups as shown in Figure 2.9. The lateral pterygoid muscle is divided into a superior and inferior heads. The inferior head originates from the outer surface of the lateral pterygoid plate while the upper
head originates from the infratemporal surface of the sphenoid bone. Both heads insert onto the anterior neck of the condule and the capsule of the TMJ. The lateral pterygoid is activated during jaw opening to cause forward protrusion. The digastric muscle is the primary jaw opener causing the jaw to hinge downward when contracted. The anterior belly of the digastric originates from the digastric fossa on the lower border of the mandible. The posterior belly originates from the mastoid notch on the temporal bone. These muscle fibres connect and form the intermediate tendon which is connected to the hyoid bone through a fibrous loop, creating pulley-like mechanism. The geniohyoid muscle originates from the inferior mental spine on the inner surface of the mandible and runs backward inserting on the front portion of the hyoid bone. The mylohyoid is a thin sheet of muscle that forms the floor of the mouth originating from the mylohyoid line of the mandible. The posterior fibres insert into the front of the hyoid bone, while the anterior fibres attach to a median fibrous raphe. During swallowing the mandible is braced and activation of the opener muscle groups causes elevation of the laryngeal complex.

The stylohyoid muscle does not function in jaw opening, but belongs to the larger grouping, termed the "suprahyoid muscles". The stylohyoid muscle has a similar placement as the posterior digastric, but originates from the styloid process (anterior to the posterior digastric origin) and forms the fibrous loop for the digastric at its insertion on the lateral side of the hyoid bone.



Figure 2.9: Jaw opening muscle groups: lateral pterygoid, digastric, mylohyoid, and geniohyoid [53] (© Elsevier, 2003, adapted with permission).

Infrahyoid Muscles

The infrahyoid muscle group encompasses all muscles that attach the hyoid bone to the cricothyroid complex, clavicle, and sternum. The relevant muscle groups include the thyrohyoid, sternohyoid, omohyoid, and sternothyroid muscles. These muscles function to depress and stabilize the laryngeal complex. Internal to the larynx are the cricothyroid, posterior cricoarytenoid, and transverse arytenoid muscle groups that contract to cause articulation of the thyroid and arytenoids with the cricoid bone.

Muscle Architecture

A detailed dissection study by van Eijden et al. [78] characterized the physical architecture of the mandibular muscles. It found that the jaw closer muscles

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to have a number of common architectural characteristics including short muscle fibres, large percentage of tendon tissue, large pennation angles, large cross sectional sizes, and relatively large mass, which are all indicative of physiological design for large force generation. In comparison to the closers, the opener and suprahyoid muscles were found to have smaller cross sectional sizes, smaller percentage tendon tissue, smaller pennation angles, and longer fibre lengths. These physiological features suggest the openers are designed for larger excursion and higher shortening velocities.

2.1.4 Surrounding Anatomy

The tongue and facial tissues are the important surrounding anatomy that apply forces on the mandible and hyoid. A mid-sagittal cross-section of the orofacial anatomy during swallowing is shown in Figure 2.10. The tongue is a large deformable organ that is the main determiner of oral cavity shape. It is composed of a number of grouped intrinsic muscles and connected to surrounding orofacial rigid structures through a set of extrinsic muscles. The genio-glossus muscle accounts for the bulk of the tongue tissue. Its fibres originate from the superior genial tubercle on the rear surface of the lower mandible, radiate widely in the tongue body, and insert into the median dorsal of the tongue from tip to base. The hyo-glossus, palato-glossus, and stylo-glossus extrinsic tongue muscles connect the tongue to the hyoid bone, hard palate, and sytlo-process of the temporal bone respectively.

The tongue plays a major role in mastication by breaking up food as well as forming and positioning the food bolus between chewing strokes. During swallowing, the tongue presses upward against the palate and contracts in a

wave-fashion to push the bolus backward to the pharynx (see Figure 2.10).

The cheeks and lips are also important anatomy surrounding the jaw and are composed of layers of skin, fatty-tissue, and muscles. During mastication and swallowing the lips seal off the oral cavity, which is particularly important for a liquid bolus. The buccinator muscles in the cheek work with the tongue to position the bolus during mastication. The lips also play a critical function in the production of many speech sounds.

The lips and facial muscles are not attached to the mandible and therefore do not apply forces directly; however, the presence of soft tissue surrounding the jaw acts as a damping force on its motion.

Our infra-mandibular model follows previously published jaw models by using a general damping term to represent the functional effect of surrounding facial tissues on the jaw. We currently omit the tongue. However, we are working on integrating a muscle-actuated deformable tongue model (see future work section 6.2.2). The addition of an active tongue model would have the greatest dynamic effects on swallowing as the back of the tongue body is anchored to the hyoid bone and involved in laryngeal elevation.



Figure 2.10: Mid-sagittal cross-section of the oral cavity during swallowing showing closed lips, upward displaced tongue, clenched jaw, and elevating hyoid [71] (© Mosby, 1961, adapted with permission from Elsevier).

2.2 Previous Jaw Modeling Approaches

The anatomical complexities presented in the previous section have significance for the decisions required in modeling the complete system. In this section we look to previous types of jaw modeling approaches to justify our choice of dynamic computational modeling of the integrated jaw and larynx.

Previous to advent of computational modeling, jaw modeling efforts can be categorized as mechanical models that physically recreate the jaw system and simple mathematical models that virtually recreate the jaw system. Mechanical models were the the earliest type of jaw modeling, which date back to the late 1800s with Alexander Graham Bell's *Talking Head*. Modern robotic jaw systems are motor-actuated to generate physical jaw motion and forces, which can be used to study the mechanics of the anatomical system. Passive mechanical devices can be used to mechanically mimic human jaw kinematics. The dental articulator is a common such device used in modern dentistry.

Modern computer technology has enabled the development of complex mathematical representations of the jaw system. Computational methods have many advantages over mechanical systems, most notably the flexibility afforded by mathematical models to be adapted to the specific craniofacial structure of individual subjects. Kinematic computational models are concerned with representations of jaw motion, whereas dynamic computational models are concerned with physics-based mathematical representations that relate inertia, forces, and motion using Newtonian dynamics.

2.2.1 Mechanical Jaw Models

Mechanical jaw modeling attempts to create a physical representation of the human mandibular system. A small number of research attempts have been made to create motor-actuated robotic jaw systems, while passive mechanical devices that capture patient-specific jaw representations are widely used in clinical dentistry.

Robotic Jaw Systems



Figure 2.11: Robotic jaw systems: (a) the Waseda-Okino Jaw Robot, (b) the University of British Columbia Robotic Jaw

Two projects have developed 6 degree-of-freedom (DOF) robotic, motoractuated mechanical jaw models and are pictured in Figure 2.11. The Waseda-Okino Jaw Robot (WOJ-1) is actuated by motor-driven wires that represent the full-compliment of mandibular muscles. It has been used to physically study mastication mechanics. The University of British Columbia Robotic Jaw [20] is small enough to be enclosed within a human skull and is capable of highly exaggerated jaw kinematics for studying audio-visual speech perception. Its linear, zerobacklash motors are fast and smooth, but do not have correspondence with the physical mandibular muscles.

Dental Articulator

A dental articulator is a mechanical device used in clinical dentistry to simulate a patient's jaw motion and occlusion. It is primarily used in the design of dental prostheses "on the bench", but is also applied in both the diagnosis and treatment of temporomandibular disorder.

Dental casts are made from recorded impressions of the patient, and mounted onto the articulator, which is adjusted and then physically manipulated to simulate patient jaw motion and occlusion.

A non-adjustable articulator is the simplest version of the device and recreates hinging jaw motion alone. It can only be used to reproduce a single occlusion position.

A semi-adjustable articulator, pictured in Figure 2.12, has a more complex mechanical structure in order to duplicate condylar motion. A typical device will have three adjustments: condylar inclination (representing the angle of the articular eminence), medial wall angle (affecting the angle of inward condylar motion), and intercondylar distance (representing the posterior width of the mandible). Wax bite imprints are taken of the patient at a number of static jaw positions and used on the mounted dental casts to calibrate the articulator's adjustments. Once calibrated, the articulator is

able to replicate the mechanics, range of mandibular movement, and occlusion of the patient. Dental protheses (e.g. bridges or crowns) are first fitted on the dental casts in the articulator to reduce the refinement time required when implanted in the patient.

A fully-adjustable articulator has even greater complexity and adjustibility. Continuous patient motion records are obtained with pantographic tracing, as opposed to a few discrete postures as with the semi-adjustable device. Adjustments on the articulator are time consuming, but can be made such that the mechanical device exactly matches the pantographic recordings, creating a highly accurate facsimile of the patient's jaw kinematics.



Figure 2.12: A typical semi-adjustable dental articulator: (a) the device with mounted dental casts, (b) close up of the spherical condyle with three planar mechanical constraints [73].

Mechanical Actuation

Both robotic systems and dental articulators are able to represent the mechanics of the jaw system; however, the dynamics of muscle-based actuation are difficult to emulate. Robotics systems may have motor-actuators that mimic physical muscle groups or may be programmed such that their motors produce only physically plausible jaw forces. Dental articulators are physically moved by forces applied to the device by a dentist's grasp, which can generate force magnitudes and directions that are not possible from the musculature of the anatomical system. An advantage of our computer model of jaw mechanics is that it is realistically muscle-actuated and therefore can recreate the limitations of the physical jaw system.

2.2.2 Kinematic Jaw Models

Numerous kinematic models of jaw motion have been reported that represent recorded motion in reduced dimensions. Ostry et al. published kinematic recordings that show three predominant, independent degrees of freedom during speech motion [58] (see Figure 2.13). Weingartner and Dillmann developed a kinematic jaw model that maps jaw motion into three axes of rotation [82]. Another widely used kinematic representation of jaw motion is the instantaneous helical axes method, proposed by Gallo [21], which has been used to infer TMJ motion [10]. Purely kinematic models of the jaw system are useful, but lack the underlying physics-based mechanics required to relate structural motion to muscle, joint, and bite forces. Our model uses Newtonian-mechanics to explain the dynamic nature of the system: muscle and joint forces cause motion of the mandible.



Figure 2.13: The Ostry et al. kinematic jaw model showing the reference frame and recorded jaw motion data during speech [79] (© Elsevier, 1995, reproduced with permission).

2.2.3 Dynamic Jaw Models

Computational models of the human jaw have been used to study various aspects of jaw biomechanics including joint dynamics, bite forces, muscle dynamics, and passive muscle forces. Physics-based jaw models represent the mandible bone as a rigid-body, the temporomandibular joint as a mechanical joint or contact surface, and the jaw muscles as tension-producing straightline actuators.

The earliest dynamic models of the human jaw system were used to study the relationship between jaw structure and bite force during static toothclenching [35] [6]. Subsequent studies have extended the analysis of bite force

generation to dynamic jaw motions [56]. Prediction of muscle contraction patterns that give rise to bite forces during clench [57] and closing [45] have also been reported.

An extensive body of jaw modeling research has been published by Koolstra and van Eijden from the University of Amsterdam (see review article [30]). Their models have developed with FORTRAN libraries, and more recently with a commercial software package, Madymo [50]. Their original model was used to study muscle dynamics during free jaw motion [31] [32] and is pictured in Figure 2.14a.

Another major contributor to jaw modeling research is a research group from the University of British Columbia. Its jaw model was developed with a commercial computer aided engineering software package ADAMS [4] and is pictured in Figure 2.14b. The group's work focused on passive muscle properties [63], wide jaw opening [62], and mastication simulation in humans [39] and pigs [40].

An alternative approach models the jaw and hyoid system based on the equilibrium point hypothesis and uses motor commands to control the model's individual degrees of freedom [38]. It has been used to study jaw motion in speech, including neuron-motor control [65] and the effects of jaw stiffness [69], head motion [68], and gravity [67]. This model incorporates sophisticated muscle dynamics, but does not attend to Newtonian rigid-body dynamics in as rigorous a manner as physics-based models mentioned above.

The previously published dynamic models discussed above have focused on the jaw system in isolation. Less attention has been paid to the submandibular anatomy, and virtually none has been paid to interactions with





Figure 2.14: Two related dynamic computational jaw models: (a) Koolstra and van Eijden (Amsterdam, The Netherlands) [32] (© Elsevier, 1997, reproduced with permission), (b) Peck, Langenbach, and Hannam (British Columbia, Canada) [63] (© Elsevier, 2000, reproduced with permission).

the laryngeal structures. Further, the tongue is a large muscular body that also applies significant forces on both the jaw and hyoid and has been neglected in previous models. Our model extends the state-of-the-art by modeling the entire infra-mandibular region and analyzing interaction forces between the jaw and hyoid during simulated jaw movement. Our modeling system is also capable of incorporating a dynamic tongue model, which will be a significant advancement of the art. In addition, the software systems designed in previous jaw models have not place significant emphasis in creating a full featured user-interface that enhances researcher capability to create and modify motion simulations.

The main advantage of dynamic models is that they have an underlying anatomical representation that can be used to relate anatomical structure to

function in order to explain the biomechanics of the system. We have chosen computational dynamic methods for our jaw and laryngeal model based on the combination of modeling flexibility and biomechanical analysis afforded by the technique.

2.3 Dynamic Jaw Modeling

As discussed in the previous section, dynamic computational modeling is useful for capturing anatomical biomechanics. It has been employed in previous jaw modeling studies and we use the technique in our jaw and laryngeal modeling system. This technique has also been used to model other musculoskeletal systems including: the lower back [47], lower limb [85], upper limb [77] [23], face [76], and whole body [13] (see [61] for a review).

In this section we provide additional details regarding dynamic computational modeling and its application in anatomical modeling. We begin with a brief explanation of the technique's mathematical underpinnings, including the forward dynamics equation and numerical integration. We begin with the basic formulation of Newton's second law (F = ma) as the foundation for forward dynamics equation and show its expansion for more complex dynamical systems. Anatomical sub-components of the jaw system give rise to additional terms in the dynamics equation; therefore we will discuss modeling these sub-components. We detail previous approaches used in dynamic modeling of human soft-tissues, muscles, and the temporomandibular joint, which provides a context for the modeling decisions made in the construction of our model presented in Chapter 3.

Anatomical data is critically important to the construction and simulation of dynamic anatomical models. We will conclude this section with a discussion of the available data types used to characterize anatomical systems and the specific published datasets we have utilized in our modeling efforts. Anatomical data was used in the construction of our model, while functional data was used to inform and verify our validation simulations.

2.3.1 Dynamic Modeling Mathematics

Dynamical modeling is the process of formulating a mathematical equation that represents a physical system governed by classical Newtonian dynamics: F = ma. The characteristics time-varying dynamical system can be captured by an ordinary differential equation, which, given a set of initial conditions, will completely describe its behaviour. Numerical integration techniques are required to solve the dynamics equation for the position of bodies over time.

Forward Dynamics Equation

Dynamic models share the same Newtonian physics-based principles to describe the dynamic nature of the physical anatomical system. A typical second-order dynamics equation for a single body is given by:

$$F_{muscle} + F_{constraint} + F_{external} = Ma + Dv \tag{2.1}$$

where F_{muscle} and $F_{constraint}$ are the 6D forces applied by the muscles and constraints respectively, $F_{external}$ is a term that encompasses gravity and forces from connected bodies, a and v are the linear and rotational acceleration and velocity of the body, M is the body's spatial inertia matrix, and D is a rigid-body damping coefficient.

Equation 2.1 is solved for body accelerations and integrated numerically to compute body velocities and body positions. The forward dynamics equation is:

$$a = M^{-1} \left(F_{total} - Dv \right)$$
 (2.2)

This is termed a "forward dynamics equation" because it relates forces to

motion: given known forces and properties of the system (mass and damping) we solve for the resulting body motion. An inverse dynamics equation is just the opposite: given body motion (velocity and acceleration) and properties (mass and damping), we solve for the forces in the system that give rise to the prescribed motion. The inverse solution is typically highly difficult or impossible to find due to redundancy.

The dynamic jaw model presented in this thesis utilizes the forward dynamics formulation to capture the mechanics of the human jaw system. Section 3.3 describes the components that give rise to terms in the the dynamic equation for the jaw model.

Numerical Integration

The forward dynamics equation (2.1) is classified as an ordinary differential equation (ODE). Numerical integration is a technique of computing the solution to the ODE incrementally given a set of initial conditions. Various numerical integration techniques are possible and are compared based on their accuracy and stability in solving a given ODE. Accuracy is a measure of closeness between the result of the numerical integration solution and the analytical solution. Stability is a measure of the largest integration timestep possible that maintains a well-behaved solution. Methods of numerical integration are generally classified into explicit and implicit schemes.

Explicit Methods. Forward Euler is the simplest form of explicit numerical integration. It is first order accurate using a linear approximation to extrapolate from the system state at a given iteration.

Given a first order ODE of the form

$$\frac{dx}{dt} = v(x,t) \tag{2.3}$$

the Forward Euler approximation of the system at iteration n+1 is given by

$$x_{n+1} = x_n + \Delta t \ v(x_n, t_n)$$
(2.4)

The Forward Euler approximation is diagrammed in Figure 2.15. Although simple and cheap to compute, the Forward Euler scheme is highly unstable [9].



Figure 2.15: Plot showing a function x(t) and approximation $\tilde{x}(t_{n+1})$ made by Forward Euler numerical integration method

Higher order explicit schemes, such as Runge Kutta, include higher order

terms in the Taylor Series approximation of the system:

$$x_{n+1} = x_n + \Delta t \frac{dx}{dt} + \frac{\Delta t^2}{2} \frac{d^2 x}{dt^2} + \frac{\Delta t^3}{6} \frac{d^3 x}{dt^3} + \dots$$
(2.5)

The third order Runge Kutta method is included in Appendix B.1. Higher order Runge Kutta schemes achieve higher accuracy and a larger stability region, but are more expensive to compute than the simple Forward Euler method. Fourth order Runge Kutta (RK4) is generally considered the breakpoint for highly accurate explicit integration [9].

Implicit Methods. Backward Euler is the simplest form of implicit numerical integration. It is a first order accurate linear scheme, similar to Forward Euler, but interpolating from the predicted derivative at the next iteration:

$$x_{n+1} = x_n + \Delta t \ v(x_{n+1}, t_{n+1}) \tag{2.6}$$

If v is linear than the system of linear equation can be solved directly. If v is non-linear the system may be approximated with linear equations, which is termed a "semi-implicit" scheme [9]:

$$v(x_{n+1}) \approx v(x_n) + \frac{\partial v(x_n)}{\partial x}(x_{n+1} - x_n)$$
(2.7)

Symplectic Euler is semi-implicit scheme for a second order ODE that solves for velocity and position at staggered timesteps. Velocity is computed with a standard Forward Euler

$$\dot{x}_{n+1} = \dot{x}_n + \Delta t \ \ddot{x}_n$$

and is used to update the position with an implicit step

$$x_{n+1} = x_n + \Delta t \ \dot{x}_{n+1}$$

which increases solution stability.

The implicit integration solution may be computationally expensive for large systems as it involves the inversion of a full system matrix; however, the form of the system matrix, including its structure and sparsity, can be utilized in the solver for more efficient computation. For example, conjugate gradient is an iterative technique that performs well for solving sparse, symmetricpositive-definite matrices. Implicit integration schemes are guaranteed to remain stable for any size timestep. This enables fast simulation rates, but may add unrealistic damping into the system producing inaccurate results.

Dynamical Components

The numerical integration methods presented in the previous section are necessary for solving the differential equation representing a dynamical system. The mechanical sub-structures of a dynamical system give rise to force terms in its dynamics equation (see equation 2.1). Similarly, the anatomical sub-components of the human jaw system give rise to force terms in the dynamics equation of our jaw model. The implementation of our model's sub-components is described in section 3.3. In the following section we provide a discussion of previous approaches to modeling jaw sub-components in order to provide context for our modeling decisions.

2.3.2 Soft Tissue Modeling

Dynamic jaw models are composed of rigid-body structures connected by force-generating muscles. Typically the soft tissues of the face and surrounding anatomy are incorporated by applying damping forces opposing jaw velocity. Realistic soft tissue mechanics are important for modeling the tongue and for sophisticated modeling of the temporomandibular joint. For our infra-mandibular model the soft connective tissue of the larynx is important as it has a significant impact on the motion of the laryngeal rigid structures. The two main techniques for modeling soft tissue are spring-mass networks and Finite-Element Methods (FEM).

Spring-mass networks approximate continuous viscoelastic deformable volume as a set of mass points interconnected by spring-damper elements. The linear lumped parameter model is inexpensive to compute; however, it is susceptible to instabilities under large deformation, manifested as internal oscillations and element inversions. Spring-mass modeling has been used in a biomechanical model of the human face [76] and in deformable models for surgical simulations where high simulation rates (100 Hz) are required [11].

FEM models discretize a deformable solid into a volumetric mesh and distribute the viscoelastic and inertia properties of the solid over each volume element. Another FEM approach uses lumped mass points at the mesh nodes, while the volume elements incorporate the viscoelastic distribution. The FEM technique is more accurate representation of solid mechanics and more stable under deformations, but also much more computationally expensive.

Although we approximate the mandible bone as a rigid-body because we are concerned with dynamic jaw motion, a few previous jaw modeling

efforts have examined the deformation of the mandibular bone using FEM models [37] [81].

2.3.3 Muscle Modeling

The dominant method for modeling skeletal muscles is with "line-type" models that apply force along a line between the muscle's origin and insertion. In such a formulation the muscle attachment areas are approximated by single points, creating a straight line of action representative of the muscle's main fibre direction. The straight-line approximation holds well for mandibular muscles, which are mostly unobstructed between their origins on the skull and insertions on the mandible, but not as well for other anatomical systems, such as the shoulder, where muscles wrap around bony structure [46].

The simplest model of muscle biomechanics is a linear spring-damper element that exhibits linear visco-elastic forces on the muscle end points. However, the spring-damper approximation does not capture the experimentally measured force-length and force-velocity characteristics of the human muscle. The combination of contractile muscle fibre and passive tendon tissue in the human muscle requires at least a three-element model to capture its complexity. This type of model was introduced by Hill [84] (see Figure 2.16) and is widely used in dynamic modeling of musculoskeletal systems, including previous jaw models.

Peck et al. performed an optimization study with their jaw model to illustrate that passive tension in the jaw closer muscles must be less than predicted by the original Hill formulation for the jaw to achieve maximum wide gape in simulation [62]. The Langenbach and Hannam jaw model's



Figure 2.16: The Hill-type muscle model representation [28]: (a) mechanical schematic, (b) force-length characteristics.

implementation of the Hill-type actuator required separate fibre and tendon components connected in series by a "zero mass particle" [39], which is numerically undesirable.

We have developed a Hill-type muscle model (see section 3.2.2) that adopts the passive tension characteristics of the Peck et al. study, and is implemented with a unified mathematical relationship that avoids the numerical instability associated with the discretized Langenbach approach.

A more sophisticated approach for modeling the 3D nature of mandibular muscles would require volumetric muscle models and realistic attachment areas. A previous study on the deformation of the human mandible during static tooth-clench used muscle attachment areas specified by groups of surface nodes on a FEM mesh of the mandible [36]. Recent efforts have developed volumetric muscle models using FEM meshes [75]; however, these

models are computationally expensive and do not incorporate the contractile characteristics within the FEM formulation. A technique for simulating volumetric methods with contact has been used in a biomechanical model of the forearm [59]. This technique could potentially be used to modeling the multipennate layered muscles sheets of the masseter and temporalis muscles.

2.3.4 Temporomandibular Joint Modeling

The temporomandibular joint has been widely modeled in a simplified manner as an articular contact surface on the maxilla that provides guidance to the condyle during jaw motion. This type of joint model requires some form of constraint to restrict the motion of the mandible based on the articular surface. The main constraint formulations include soft constraints, reduced coordinate representations, and full-coordinate representations with constraint forces.

In a "soft constraint" formulation penalty forces are applied to a body as it penetrates a predefined surface. Typically the surface will have viscoelastic properties such that the reaction force is proportional to the penetration depth and velocity. Soft constraints have been used to model TMJ articulation in both the Peck and Koolstra jaw models. Soft constraints are problematic because penetration is required and energy is added to the system by the viscoelastic surface. Additionally, highly stiff constraints tend to make the dynamical system more difficult to integrate with explicit methods (see section 2.3.1 for discussion).

The reduced coordinate formulation uses only the number of DOFs in the constrained system to describe body motion. The reduced parameterization

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saves on computation, but it may be difficult to formulate. Additionally, such a procedure is not extensible with changes in contact. For example, the jaw system constrained by two TMJ contacts to create a 4 DOF system and its DOFs are further reduced during tooth contact. Reduced coordinate representations have been used in kinematic jaw models to describe recorded jaw motion in less than 6 DOFs; however, such a scheme has not been used in dynamic physics-based jaw models. This is most likely because the jaw system has a small number of DOFs and thus the computational efficiency gain of a reduced coordinate description over full coordinate description are minimal.

Full coordinate representation describes the system in all of its unconstrained DOFs. Constraint equations are used to restrict the motion and velocity of bodies to a subspace of the free system. The implementation of rigid-body constraints for our jaw model is described in section 3.2.1.

Both linear and curvilinear articular surfaces have been used in previous jaw models and Peck et al. have reported that the linear approximation has a relatively small effect on motion during simulated jaw opening [62]. We have implemented a linear constraint and found it had limitations recreating complex condylar motion required during mastication motion.

In addition to a frictionless articular constraint surface other mechanisms have been used in previous TMJ models to restrict lateral and posterior condylar motion. In their study of muscle-activated jaw movements, Koolstra and van Eijden [33] included a "temporomandibular ligament", modeled as an inextensible wire between the lateral pole of the condyle and the articular eminence, to limit lateral excursion of the condyle. Langenbach and

Hannam [39] also constrained working-side condylar motion with a "temporomandibular ligament" (exponential tensile properties). They also included an additional "medial wall" for the balancing-side condyle, although they reported that it was not used during unilateral chewing. We use two unilateral rigid constraints to provide medial and posterior guidance and propose that the three constraint surfaces could be replaced with a 3D curvilinear constraint surface as a future extension of our model.

As described in section 2.1.2, the actual TMJ anatomy is much more complex than a simple smooth contact surface. The condyle is separated from the articular surface by a layered cartilaginous disc that deforms to distribute forces between the irregularly shaped bony surfaces. FEM modeling has been used to analyze the mechanics and force distribution of the articular disc in [7] and [14], and to model pathology related to disc-ligament connections in [12]. Recently, Koolstra and van Eijden have integrated FEM disc modeling with a dynamic rigid-body jaw model using a commercial software system for combined simulation of combined rigid and deformable bodies [50]. A sophisticated FEM disc model is required for accurate predictions of joint force distributions, but has not been the focus of our jaw modeling efforts to date. It does however remain a viable avenue for future work as the ArtiSynth modeling software supports fast FEM modeling techniques.

2.3.5 Modeling Data

Recorded data is a critical component for generating realistic anatomical models as well as simulating and validating their function. Our jaw model incorporates multiple data types and a mix of subject-specific recordings and

average-valued human data from previous studies. In this section we discuss data types and important studies that have reported relevant anatomical and simulation data.

Data Types

The historic method of garnering anatomical data is through cadaver dissection and physical measurement. This approach is still widely used and is the basis for the main corpus of medical anatomical records. Modern techniques for gathering anatomical and physiological data are dominated by medical imaging technologies. Various medical imaging techniques exist and each have particular advantages in terms of target tissue type, spatial resolution, imaging rate, contrast, and signal-to-noise ratio (SNR). Examples of the dominant imaging modalities are pictured in Figure 2.17 and summarized in Table 2.1 having been compiled from Prince and Links [64] and Fitzpatrick et al. [19]. This section is intended as a brief introduction to the medical imaging in order to provide context for the data sources used to inform our model's construction and simulation.

Magnetic resonance imaging (MRI) uses a strong magnetic field to produce 3D volumetric images of human tissue. It can capture high-resolution (1 mm³ voxel) images of tissue by measuring signal attenuation, making it ideal for imaging soft-tissue structures. Dynamic MRI sacrifices resolution for capture speed enabling imaging of dynamic physiological actions at rates up to 10 Hz. Ultrasound imaging uses echos from pulsed ultrasound waves emitted into tissue to determine tissue impedance. Ultrasound is well suited for imaging soft-tissue; however, it typically provides images with lower SNR

than MRI. The advantage of ultrasound imaging is that it captures at high frequency, enabling imaging of dynamic tissue motions. High resolution, high SNR ultrasound images and 3D reconstructions can be computed from processing multiple 2D ultrasound slices.

X-Ray imaging uses radiation in the x-ray wavelength to capture high contrast 2D images of dense tissue, and is typically used to image bony structures. Videofluoroscopy uses temporal averaging to perform dynamic xray imaging at rates up to 60 Hz. Computed-tomography (CT) uses a large number of radially arranged x-ray image slices to compute 3D volumetric data of dense tissue. CT imaging provides the highest contrast, spatial resolution (0.5 mm³ voxel), and SNR for images of 3D bone structure. The drawbacks of CT imaging are that it exposes a patient to a significant dose of radiation and only provides static images due to the long capture time. Cone-beam CT imaging is widely used in dentistry to image the craniofacial structures and provides the highest resolution possible for CT technology.



Figure 2.17: Example data for different medical imaging modalities: (a) mid-sagittal MRI image of orofacial anatomy [15], (b) Ultrasound image of tongue surface, (c) CT image slice in coronal plane (top view) showing u-shaped mandible.

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Motion tracking systems are used to capture kinematic data for physical human actions. Optical tracking systems use an array of video cameras to capture the 3D motion of active (light-emitting) or passive (light-reflecting) markers fixed to the moving body. Multiple rigidly connected markers can be used to compute the 6D motion (position and orientation) of a body, such as jaw motion, while large marker arrays are used to track deformation, such as surface facial motion. Magnetic tracking systems detect the 6D position and orientation of markers within an emitted magnetic field. Although magnetic tracking provides direct 6D data, optical systems are generally preferred for medical applications for their greater accuracy and sampling rates.

Type	2D/3D	Target	Max	Spatial	Signal-	Rad
		Tissue	Rate	Resolution	to-Noise	Dose*
XRay	· 2D	Hard	static	high	high	low
VF	2D	Hard	60 Hz	high	high	high
CT	3D	Hard	0.1 Hz	high	high	high
MRI	3D	Soft	10 Hz	med	med	none
US	2D/3D	Soft	200 Hz	med	low	none
MT	3D points		500 Hz	high		none

Table 2.1: A brief summary of the dominant data types used to characterize the structure and motion of anatomical systems. Sources include traditional x-ray (XRay), videofluoroscopy (FV), computed tomography (CT), magnetic resonance imaging (MRI), ultrasound (US), and motion tracking (MT). *Rad Dose refers to the radiation exposure caused by the imaging technique.

Muscle activity during physical human action is measured with electromyography (EMG) recording. EMG recordings are made with either surface electrodes attached to the surface of the skin above the muscle or with wire electrodes inserted directly into muscle tissue. Surface EMG is highly sensitive to differences in skin preparation, while wire EMG is highly inva-

sive. Wire EMG achieves better signal-to-noise ratios than surface EMG, however both are susceptible to cross-talk between adjacent muscle groups. Another deficiency of EMG recording is that signal amplitudes are sessiondependent and therefore only provide accurate information about timing of muscle contraction and relative activation profiles.

Anatomical Data

Relevant data for modeling the jaw anatomy includes dynamic properties of mandibular muscles, inertia of the mandible, and structural geometry of the infra-mandibular skeleton.

Muscle Properties. The dynamic properties of mandibular muscle groups have been described in detail by van Eijden et al. [78]. Physical measurements made on six cadavers of average craniofacial anatomy provided data for muscle rest length, maximum muscle stretch, cross-sectional size (which has correspondence to the maximum isometric force production capability), main fibre directions, and muscle attachment locations. These muscle properties have been adopted in our model and are summarized in Appendix A.3.

MRI imaging is a viable modality for determining subject-specific muscle data. MRI provides adequate resolution to approximate muscle lengths, cross-sectional sizes, and attachment areas; however, processing techniques require significant manual effort. Another problem with determining muscle attachment area from image data is that muscles may be attached to a subset of their contact area with a bony structure, which is difficult to differentiate with a single image set.

Mandible Inertia. The mass of the mandible varies widely among adult individuals within the range of 200 g to 300 g. The inertia properties of the mandible have been reported by Korioth and Hannam in a finite-element analysis and measurement of a CT-imaged mandible from a adult human cadaver [36]. These inertia properties have been adopted in our model and are summarized in Appendix A.2.

Skeletal Geometry. CT imaging is the "gold standard" approach for 3D reconstruction of skeletal geometry. It is widely-used in research and clinical studies having the highest resolution and contrast for imaging bony-structure. Segmentation of individual bony features is possible with semi-automatic methods with medical image manipulation software, such as Amira [3] and ITK [29]. Clean, well-behaved meshes of segmented bodies are desirable and must be manually constructed to match the noisy segmented data. We have recorded cone-beam CT data and integrated it into the skeletal geometry of our model as described in section 3.2.3.

CT data does not provide enough detail to easily extract tooth crown details. An alternative approach for accurate dentition meshes is to create dental casts for a subject and use laser-scanning technology to create accurate meshes of the casts.

Functional Data

Functional data includes all forms of data gathered from recordings of jaw function that can be used as input to a model to simulate similar functional tasks.

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Jaw Border Movement. The mid-incisor point on the lower jaw is the most widely used landmark in motion recordings because its position is easy to track. The maximum range of jaw motion is describes as the "maximum motion envelope" or "border movement" of the mid-incisor point of the jaw (see Figure 2.18). Mid-line border movements are common and 3D border movements have also been reported. Mid-line border movements are anchored by four kinematic positions: intercuspal clench, maximum forward protrusion, maximum hinge opening, and maximum opening. These kinematically derived border movements may not be achievable under muscle activation: for example, maximum hinge open without forward protrusion. The jaw's range of motion under muscle activation in terms of incisor point displacement is given in Table 2.2.

Movement	Condylar Motion	Incisor Motion
Rest Position	0 mm	5 mm
Max Protrusion	10 mm; 0°	10 mm
Max Open	6 mm; 30°	50 mm

Table 2.2: Typical values for jaw rest position, maximum forward protrusion, and maximum wide opening. (Modified from [62])

The jaw's natural gape at upright rest is termed the "rest position" and is typically in the range 3-5 mm. Peck et al. reported that a low level activation, or "active tone", is required for the jaw to move to a typical rest posture under gravity (see Table 1 in [62]).

Langenbach and Hannam report that their model achieved a maximum gape of 38 mm in an upright posture [39], while Peck et al. report a maximum

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Figure 2.18: Mid-sagittal trace of mid-incisor point showing maximum range of jaw motion, known as the Posselt figure. The figure shows hinge opening (A), the tooth-controlled border (B), maximum protrusive opening (C), maximum gape (D), the Intercuspal Position (IP), maximum protrusion (MP), and the Rest Position (RP).

gape of 45-51 mm by lessening the passive muscle forces in their model [62]. Koolstra and van Eijden studied the function coupling of head and jaw motion in [34] and reported that a realistic maximum gape of 50 mm was achieved with a backward head rotation of 15° . We use these previously published results to validate the dynamic range of jaw motion of our model, as shown in section 5.1.2.

Mastication Motion. Jaw motion during mastication has been well characterized in the literature. The Ahlgren mastication envelope is widely used representation of human mastication. Ahlgren recorded 3D mid-incisor point motion for a large subject-set and range of chewing conditions and reports

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average motion traces in the frontal and sagittal planes for typical mastication [1]. These mastication profiles have a tear-drop shape as shown in Figure 2.19 and vary among individuals and food type. Recordings of jaw movement with modern 6 DOF optical tracking systems support the original Ahlgren incisor point trajectories, but are also able to characterize condylar motion during mastication. During the closing phase of unilateral chewing the condyles move differentially; the working-side condyle returns to the articular fossa before the balancing-side condyle [44] [48] [60]. As the balancing-side condyle slides backward, the working-side condyle rotates in its fossa producing lateral slew at the incisor point and interocclusal forces to crush the food bolus.



Figure 2.19: The Ahlgren chewing cycle showing a typical tear-drop shaped trace of the mid-incisor point in frontal plane during normal mastication motion [1].

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Mastication Muscle Activity. EMG recording has been used to characterize the pattern of muscle activity dynamic jaw motions such as speech and mastication. Moller performed the most extensive study of muscle contraction patterns during speech, using a combination of surface and wire EMG to record all jaw muscle groups during a series of chewing trials, with a set of twenty subjects with normal craniofacial structure [49]. Moller standardized recording locations and skin preparation in order to obtain signals comparable across subjects, and reports the average contraction pattern for his subject-set (see Figure 2.20). He goes on to compare his average-valued normative dataset to recordings from subjects with craniofacial abnormalities in order to characterize the way in which their muscle activity is atypical.

Mastication EMG studies have also been performed by Hannam and Wood to specifically study the activity of the medial pterygoid muscle [26], which is difficult to record from due to its location on the inner side of the mandible, as well as the lower head of the lateral pterygoid [83]. The lateral pterygoid study is important because it reports that the muscle is entirely inactive during the closing phase of the chewing cycle, which contradicts Moller's original work. This work suggests that Moller's recording of the lateral pterygoid suffered from crosstalk with the adjacent anterior temporalis muscle fibres.

Recent EMG recording studies from Murray et al. [51] report that the upper and lower heads of the lateral pterygoid muscles are heterogeneous and functionally co-contract. This study also supports the notion that the lateral pterygoid muscle is inactive during closing and belongs to the group of "jaw opener" muscles. Murray et al. also reports a sophisticated technique



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Figure 2.20: Muscle activation trajectories derived from Moller EMG recording for human mastication [49]. Muscle abbreviations used are as follows: posterior / anterior temporalis (PT / AT), masseter (M), medial pterygoid (MPT), lateral pterygoid (LPT), and digastric (D).

for verifying EMG wire location in muscle tissue through CT imaging after the recording session [55], which is important for differentiating between EMG signals from the adjacent muscle fibres of the upper and lower lateral pterygoid.

Laryngeal Motion. Recording laryngeal motion is more difficult than jaw motion because there is no externally available landmark, such as the teeth in the case of the jaw. X-ray imaging (chephalometry) has been used to record laryngeal motion in the mid-sagittal plane (a typical image is shown in Figure 2.21). Fink reports recordings of hyoid and thyroid position dur-


Figure 2.21: A single videofluoroscopic frame of the swallowing sequences. Markers are visible on the lips, lower-incisor, tongue, hyoid, and larynx [22].

ing swallowing and effort closure in his comprehensive analysis of human larynx function [18]. In a videofluoroscopy study of eight healthy subjects, Bülow et al. report average maximum displacements of $16.3 \pm 0.94 \ mm$ and $25.6 \pm 0.78 \ mm$ for the hyoid and thyroid respectively [8]. Gay et al. report average duration of maximum laryngeal elevation to be $258 \pm 96 \ ms$ for ten healthy subjects [22]. Muto et al. also use cephalometric measurements to characterize the motion of the hyoid bone during wide jaw opening, showing that it lowers only slightly (1-2mm) when normalized for head rotation. At maximum gape the recordings clearly show that the anterior tip of the hyoid body aligns with the lower edge of the mandible. Hiiemae et al. report comprehensive data set of tongue and hyoid motion for a range of function recorded with videofluoroscopy [27].

A 3D reconstruction of the thyroid and cricoid using high speed MRI imaging is reported in [74]. The recorded motion shows differential hingelike articulation of the thyroid and cricoid along with sound recordings that verify vocal chord stretching.

2.4 Summary

In this chapter we have exposed a wealth of information related to modeling the human jaw and larynx in order to provide context for the modeling decisions presented in the body of the thesis. We first looked to the anatomical structure and function of the infra-mandibular system to provide a grounding necessary for making modeling approximations of the physical system. We also discussed previous modeling approaches to weigh the merits of mechanical, kinematic, and dynamic models. Having discovered the benefits of dynamic modeling, we examined the technique in detail as it is the chosen method for our jaw and laryngeal modeling efforts. The mathematics of dynamic modeling is rooted in Newton's second law and requires advanced numerical computation to solve the forward dynamics equation. We also examined previous modeling of the subcomponents of the jaw system as well as the data required to make the models representative of real human anatomy.

Given the knowledge of jaw and laryngeal anatomy and modeling presented above we will now, in the body of the thesis, describe the construction of our model and its use in simulating jaw and laryngeal biomechanics.

Chapter 3

Constructing a Dynamic Jaw Model

Our three-dimensional, dynamic jaw model, pictured in Figure 3.1, is rooted in the modeling literature discussed in the previous chapter. As such, it shares a number of commonalities with previously published models; however, we have made innovations in modeling techniques that further the stateof-the-art. Our jaw and laryngeal model is part of a larger general purpose biomechanical modeling platform, ArtiSynth. In this chapter we will introduce ArtiSynth, discuss the constituent components of our jaw model, and describe the technical contributions made in its development.

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Figure 3.1: Our jaw and laryngeal model showing the skeletal components connected with straight-line muscles and connective tissue, as well as constraint planes at the temporomandibular joint and upper teeth.

3.1 ArtiSynth Software

Our jaw and laryngeal model was constructed within ArtiSynth, a platform for three-dimensional physics-based modeling and simulation targeted specifically at modeling orofacial and upper airway anatomy [17].

MechModel API. The ArtiSynth *MechModel* Application-Programmer Interface (API) is a set of Java classes for building mechanical models out of component building blocks. The MechModel components include: rigidbodies, particles, rigid-body markers, lineal springs, dampers, and FEM meshes. MechModel also provides support for rendering these components in the model viewer window using OpenGL for Java (JOGL).

Core Simulation Engine. In addition to support classes for building mechanical models, ArtiSynth has a core simulation engine that solves the dynamics of such models and computes their motion over time. Simulations can include gravity and other external forces. ArtiSynth simulation engine supports multiple numerical integration schemes that can be exchanged online during simulation. The supported integration methods include Forward Euler, 4th Order Runge Kutta, Symplectic Euler, and Backward Euler, and are discuss in related work section 2.3.1.

3.2 Technical Advancements

The jaw model required additional modeling components beyond the default set provided by ArtiSynth: rigid-body constraints for the temporomandibular joint and tooth contact, a model of human mandibular muscle dynamics, and a process to integrate medical image data into the model. These technical contributions are detailed in this section.

3.2.1 Rigid-Body Constraints

The capability to constrain the motion of bodies within a dynamic rigid-body simulation is important and typically used to simulate connections or contact between bodies [5].

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We have implemented rigid-body constraints with full coordinate representation based on the Lagrangian formulation [66]. Hard constraints provide realistic reaction forces that prevent penetration of contact surfaces. We use rigid constraints at the TMJ to create a contact surface on which the jaw condyle slides and at the bite plane to prevent interpenetration of the teeth when the jaw closes.

A constraint on a body is specified as a linear subspace within the 6 degree-of-freedom (DOF) motion space where reaction forces are generated to prevent motion. In our formulation the constrained subspace is specified by G: a set of 6D force vectors (3D linear force and 3D torque), termed "wrenches". The orthogonal subspace is the region of admissible body motion and can be specified by G^T : a set of 6D velocity vectors (3D linear velocity and 3D angular velocity), termed "twists".

As an example, a planar constraint limits the motion of a body in 1 DOF, the direction of the plane normal, and therefore can be represented by a single constraint wrench. The body is free to rotate and slide along the plane; however, one point on the body is constrained to lie within the plane. The wrench that specifies a planar constraint, represented in the constrained body's coordinate frame, is given by:

$$\mathbf{g}_{6\times 1} = \begin{pmatrix} \mathbf{n} \\ \mathbf{p} \times \mathbf{n} \end{pmatrix} \tag{3.1}$$

where **n** is the normal vector of the plane and **p** is the displacement vector from the origin of the body's coordinate frame to the contact point of the body on the plane (see Figure 3.2). A reaction force is generated normal to





Figure 3.2: A schematic of the left TMJ planar constraint that gives rise to the constraint wrench in equation 3.1.

plane at the contact point that induces a force and torque on the body in the subspace spanned by the wrench, g(3.1).

If a body is subject to multiple constraints the G constraint matrix contains multiple columns of g wrenches:

$$G_{6\times m}^{T} = \begin{pmatrix} g_1 & g_2 & \dots & g_m \end{pmatrix}$$
(3.2)

where m is the number of constraints enforced on the body.

Before each integration step in the simulation, we compute a reaction force that satisfies the constraint by projecting the applied force on the body into the constrained subspace using the following equation:

$$f_c = -G^T (GM^{-1}G^T)^{-1} GM^{-1} f_a$$
(3.3)

where f_a is the applied force on the body due to inertia, damping, muscle forces, et al., M is the spatial inertia matrix for the constrained body, G is the list of wrenches specifying the constrained subspace, and f_c is the reaction force that is added to the body so that the total force acting on the body is within the subspace of admissible motion [43].

After each integration step we check for penetration of the body into the constraint, which may occur due to numerical errors. If illegal penetration has occurred, a rigid transformation is computed and applied to the body to minimize the squared distance to all constraints.

Unilateral constraints use the same formulation as presented above, however the constraint acts only in one direction. For a planar surface, a unilateral constraint acts as a collision surface, where the body is free to move above the plane, but penetration into the plane is prevented. Unilateral constraints are only added into the body's constraint matrix if they are active. The active check for a unilateral constraint is if the body's velocity is such that it will move into the constrained space within the next time step.

3.2.2 Unified Muscle Model

Human muscles are complex force generating elements that have dependency on length, rate of length change, and activation signal. The ArtiSynth *Lineal-Spring* component was extended to create a Hill-type actuator representative of mandibular muscles. The Hill-type muscle model [84] is widely used to model the nonlinear characteristics of human muscles and have been adopted by the closely related previously published jaw models [31] [39].

The Langenbach and Hannam jaw model [39] required separate compo-





Figure 3.3: The force characteristics of our adapted Hill-type muscle model: (a) force-length profile for both the fibre (active) and tendon (passive) components, (b) force-velocity profile for the linear damping component.

nents to model the fibre and tendon characteristics of the Hill-type muscle model. These separate components are attached in series by a "zero mass particle", which are numerically undesirable. Developing our model with custom code enabled us to implement both the passive, active, and damping properties of the Hill-type muscle force-length relationship mathematically in one unified muscle model. The force-length and force-velocity characteristics of our muscle model are shown in Figure 3.3. The active force generation is

$$F_{a}(l) = \frac{F_{max}}{2} \left(1 + \cos 2\pi \tilde{l}\right) \quad \text{if } 0.5 \le \tilde{l} \le 1.5 \tag{3.4}$$

where $\tilde{l} = \frac{l - l_o tr}{l_o (1 - tr)}$

and l is the muscle's instantaneous length, l_o is the muscle's rest length, tr is the ratio of tendon length to fibre length, and F_{max} is the maximum isometric force that can be exerted by the muscle (proportional to the muscle's cross-

sectional area). The parameterized passive tension curve is

$$F_p(l) = \left(\frac{\mathrm{e}^{(l/l_{max})exp} - 1}{\mathrm{e}^{exp} - 1}\right) F_{max} \times pf \quad \text{if } l \ge l_o \tag{3.5}$$

where l_{max} is the muscle's maximum stretch length, pf is the fraction of F_{max} exerted at maximum stretch, and exp is a parameter that changes the exponential curve. We use values of 0.1 and 0.0115 for exp and pf respectively for all muscles, which agrees with a study of mandibular muscle passive properties by Peck [62]. The total instantaneous force produced by the muscle is

$$F(l) = F_a(l)a(t) + F_p(l) + D\frac{dl}{dt}$$
(3.6)

where D is a linear damping term that opposes muscle shortening.

The activation input signal, a(t), currently represents the mechanical contraction level for the muscle, and thus gives rise to an instantaneous force output. The muscle model could easily be extended to use a neural excitation input signal to the muscle, which would then incorporate a time delay between muscle excitation and muscle contraction, approximating the dynamics of motoneuron activation. An additional extension to the muscle model would be to include simple feedback loops to generate responses for the unloading and stretch reflexes of the jaw system.

3.2.3 CT Data Integration

In addition to modeling technology, we require a mechanism to integrate subject-specific anatomical data. We have focused on integrating subjectspecific geometry data: bony structure and muscle attachments. We have developed a data integration process using a popular commercial image manipulation tool, Amira, and interfacing it with ArtiSynth to import extracted data into are model.



Figure 3.4: Process diagram showing the creation of jaw model geometry from CT data: (a) raw voxel data, (b) noisy segmented voxel mesh, (c) clean anatomy mesh, (d) generic anatomy mesh, (e) mesh shaped to specific anatomy, (f) registered meshes and muscle attachment location geometry.

Imaging and Extraction

We have used high-resolution (0.4 mm cubic voxel), cone-beam CT scans of a 35 year-old male with normal craniofacial and dental anatomy as an anatomical template for our model. The image data ranged from ranged from the inferior border of the orbit to the cricoid bone. Orthogonal slices of our dataset are pictured in Figure 3.5.

Our process of extracting geometry from the CT data is diagrammed in Figure 3.4 and involved the use of two additional software applications: Amira [3], a medical image visualization and manipulation software tool,





Figure 3.5: Orthogonal slices through the Computed Tomography dataset used in construction of jaw model skeletal geometry: (a) coronal plane, (b) transverse plane, (c) sagittal plane.

and Rhino [72], a 3D mesh building software package. For large bodies that were well imaged (maxilla, mandible, hyoid) we used Amira to automatically segment raw CT data and constructed clean meshes to fit the data manually with Rhino. For small bodies and anatomy outside the range of the image set, we started with a generic anatomical mesh and manually morphed it in Amira to match the subject's anatomy. All of the skeletal meshes were registered to the original dataset in Amira as pictured in Figure 3.6. The manual tasks of segmentation and mesh generation were performed by a dentist familiar with craniofacial anatomy. The high fidelity meshes were registered with the original CT dataset in Amira. Muscle attachment sites were chosen based on conventional descriptors [24] [70] and placed on mesh surfaces with Amira "landmarks".





Figure 3.6: (a) Image showing noisy segmented mandible mesh superimposed over orthogonal CT data slices. (b) The final rigid-body meshes in Amira after registration with the original CT dataset.

Data Integration into Model

The main technical contribution of our data integration efforts was the design and implementation of software to interface our ArtiSynth model with Amira. Utilizing the capabilities of Amira, as discussed in the previous section, required support methods to parse Amira data files to generate geometry data in the jaw model. For rigid-body geometry, the process involved loading meshes exported from Amira and extracting and applying transformation data from Amira script files. For muscle placement, an additional process was designed to import muscle attachment sites into the ArtiSynth jaw model as landmark sets from Amira. This enabled meshes to be loaded and registered in ArtiSynth as they appeared in the Amira scene graph, and muscle models to be generated and placed according to landmarks defined within Amira.

3.3 Model Components

The jaw model is composed of modular set of subcomponents corresponding to anatomical subsystems. The skeletal components and muscle attachment sites are created with extracted data from CT images as described in the previous section. Dynamic properties for the components have been constructed with average values from published measurements (see related work section 2.3.5).

3.3.1 Skeleton

Our model includes rigid-body structures for all the bones and cartilage in the infra-mandibular region which is diagrammed in Figure 3.7. The craniomandibular substructure includes elements for skull, maxilla, and mandible. The maxilla includes detailed bony structure for the palate, pterygoid fossae, zygomatic arches, articular eminentia and fossae, and infratemporal fossa. Our laryngeal substructure includes the hyoid bone, thyroid cartilage, cricoid bone, and arytenoids, as well as a fixed sternum to anchor hyoid and thyroid depressor muscles and a fixed vertebrae column as a landmark for anatomy registration.

The meshes for these bodies were created from CT data as described in section 3.2.3. High resolution and accurate meshes for the structural components are important for placing muscle attachment sites as well as appealing visual rendering of model motion. Very high resolution meshes created from cone-beam CT data have been optimized to maintain sufficient detail with polygon counts low enough for fast rendering on a modern desktop





Figure 3.7: The skeletal structures (bones and cartilage) in our model of the infra-mandibular system.

computer. As an example, the mandible mesh has been reduced to 15000 polygons, but still retains highly detailed geometry for the tooth crowns.

We have used masses of 200, 10, 24, and 23 g for the mandible, hyoid, thyroid, and cricoid respectively. Spatial inertia properties for the jaw model are taken from measurements of a human jaw reported in [39]. Spatial inertia properties of other bodies have been approximated from the convex hulls of their mesh geometry.

3.3.2 Teeth

Although the human dentition is composed of a series of separate tooth bodies attached to the bony structures of the mandible and maxilla by the periodontal ligament, we model the tooth crowns as being rigidly connected to the bony structure.

Bite contact is achieved by a rigid unilateral planar constraint located at the upper mid-incisor point and angled to the occlusal plane. Reaction forces are generated normal to the occlusal plane at two bilateral bite points located at the upper second molars (see Figure 3.8). Additional bite contact points could easily be added along the dental arch.

High fidelity tooth crown meshes are used for visualization, but currently the planar bite constraint models a subject with flat teeth. Our rigid-body constraint formulation does allow for general mesh-on-mesh multi-point contact between the maxilla and mandible teeth. This would require collision detection to detect contact points during intercuspation. Accurate dental contact would be potentially useful for detailed studies of three-dimensional bite forces using high resolution surface scans of dental casts. It would be computationally feasible, since it has recently been shown that contact simulation has an expected complexity of O(n), in the number of contacts, for systems with a fixed number of degrees of freedom [42].

3.3.3 Joints

The skull and mandible are connected by two temporomandibular joints. These joints are modeled as rigid bilateral planar constraints, angled down-



Figure 3.8: Our model's temporomandibular joint is composed of three planar constraints that create a "virtual dental articulator." Interpenetration of the teeth is prevented by two unilateral constraints located at the upper second molars.

ward and forward by 25° and canted inward by 5°, restricting the translation of the mandible to a planar surface, which approximates the curvilinear condylar path. Additional condyle guidance is achieved through two unilateral constraints per joint: a medial wall angled inward by 7° and an orthogonal posterior wall. The three constraints approximate the concave 3D shape of the articular fossae (see Figure 3.8).

The constraint planes have adjustable angles and locations that mimic a semi-adjustable mechanical dental articulator device. This "virtual dental articulator" TMJ model provided the additional stabilization required to handle the large joint loads that occur during simulated mastication (see section 5.1.4).

We have found that plausible free jaw motion (no tooth contact) was possible with a linear path joint constraints. We propose that a linear approximation is appropriate for simulating speech motions where the condyle remains within a flat region of the articular eminence. However, during mastication simulations we found it difficult to obtain accurate differential condyle motion in the closing phase of the chewing cycle with a planar constraint (see section 5.1.4 for discussion). Our linear path TMJ constraints could be extended to a 3D curvilinear surface with the Lagrangian technique (see future work section 6.2.1).

3.3.4 Muscles

The jaw and laryngeal model is actuated by a set of 45 straight-line muscles. The represented muscle groups include the anterior, middle and posterior temporalis, deep and superficial masseter, superior and inferior lateral pterygoid, medial pterygoid, anterior and posterior digastric, posterior mylohyoid, stylohyoid, geniohyoid, thyrohyoid, and cricothyroid muscles.

Properties for the mandibular muscles, such as maximum force magnitude, tendon-to-fibre length ratios, and passive tension characteristics, are based on published values [62]. A table of muscle properties is included in Appendix A.3. Properties of the laryngeal muscles are not well described in literature; therefore, we have chosen parameters that are arbitrarily scaled from mandibular muscles by approximate differences in muscle length and cross-sectional area.

Muscle attachment sites have been taken from medical image data (see section 3.2.3). ArtiSynth allows for modular exchange of model components, therefore simpler (linear spring) or more complex (multipennate muscle model) muscle components can be easily interchanged with the standard



Figure 3.9: The laryngeal complex during swallowing simulation showing stretch of the spring-mesh membranes allowing for larynx elevation.

Hill-type model.

3.3.5 Tissue

Soft tissue is an important part of the laryngeal system. The larynx is a highly deformable organ, that can be modeled as a chain of rigid cartilage structures connected with soft membranes that provide stability and directional compliance. We approximate the soft connective tissue as a network of viscoelastic spring elements. One spring-mesh network connects the hyoid and thyroid, representing the hyothyroid membrane, and another anchors the cricothyroid complex, representing longitudinal compliance of the trachea (see Figure 3.9). Although the laryngeal connective tissue is currently approximated by spring networks, ArtiSynth allows extension to more sophisticated finiteelement tissue models. Finite-element modeling would enable more accurate representation of the connective tissue stiffness. The stiffness properties of the larynx soft-tissue are not well described in the literature; we have used arbitrary values for spring stiffness in our current spring-networks that yield plausible laryngeal mobility.

Tissue attachment sites were chosen to represent the extent of membrane attachment to the individual laryngeal bodies based on anatomical records [24]. The membrane attachment sites were assigned using Amira and imported in the jaw model with procedure similar to that of muscle attachment sites (see section 3.2.3).

3.3.6 Food Bolus

A food bolus component was added to the model as part of the mastication simulations. The boluses can be added to any location along the dental arch and provide viscoelastic resistance when the upper and lower teeth compress. The bolus resistance is applied normal to the occlusal plane; however this resistance direction can be modified to simulate conditions of food compression or shear at different tooth locations. The bolus elements are modeled to disintegrate after the applied bite force exceeds a tolerance. This simulates crushing of food by the teeth during the closing and shear phase of the chewing cycle and reforming and repositioning of the bolus by the tongue during the opening phase. Figure 3.10 shows the graphical representation of the bolus spheres as well as a plot of bolus resistance during the chewing. The properties of each bolus are modifiable and include size, stiffness, damping, and force threshold for crushing. Also, the visual color of the food bolus sphere in the graphical display is representative of the boluses state: green is not in contact (no resistance), red is in contact and under compression (resistance proportional to compression), grey is in contact and crushed (no resistance).



Figure 3.10: (a) Our model with a left-side bolus out of contact and a rightside bolus in contact and providing resistance. (b) Plot of bolus resistance over time for a bolus with a 45 N disintegration threshold as it is crushed.

3.4 Summary

This chapter discussed the construction of the jaw model including background information on ArtiSynth, technical advancements, and implementation details of the model subcomponents. Rigid-body constraints, muscle models, and data integration methods were all developed as extensions to ArtiSynth based on the requirements of the jaw model. The constituent components of our infra-mandibular model are a rigid-body skeleton, muscles, contact at the temporomandibular joint and teeth, larynx soft tissue, and a food bolus for the model to chew.

Chapter 4

Creating a Comprehensive Simulation Interface

The previous chapter has described the technical components of the jaw model and highlighted the aspects of the model that improve upon previous work. The utility of such a model for studying jaw mechanics is unequivocally linked to its capability to be used by a researcher with expert knowledge in orofacial anatomy. The difficulty is that an expert in human physiology is typically not also a expert in the language of computer modeling. Therefore, the design of a usable, intuitive interface for a non-computer specialist is of critical importance for the model's potential as a research tool to be exploited. Our efforts to build a comprehensive user-interface to expose model properties and establish a system for fast generation of task-based simulations are chronicled in this chapter.

4.1 Jaw Simulation User-Interface

The ArtiSynth Timeline is the main simulation interface that allows for controlling inputs and observing outputs. We have developed input and output data probes for the jaw model that can be used by an expert researcher to create jaw motion simulations. The ArtiSynth API provides a set of Graphical User Interface (GUI) components, such as sliders, text boxes, buttons, and menus, that were used to create additional controls for a researcher to interact with internal model parameters. The jaw interface also incorporates controls for the way in which input data is applied to the model and visualization the model's state and output data.

4.1.1 User-Interface Requirements

We employed user-centric design practices in the development of our jaw simulation interface. This process involved the creation of a requirement specification for the interface and refinement through direct user feedback. The requirements for the jaw researcher-interface are as follows:

- A unified interface for input manipulation, simulation control, and output visualization - ArtiSynth Timeline.
- Access to modify all model parameters through the GUI as opposed to the Java API Jaw Control Panel.
- Adaptability to present a clean and clear interface for specific types of simulation Probe Grouping; Subset Control Panels.

- Immediate user feedback Output Probe Display; Automatic Update of Rendered Model.
- Fast Detailed Inspection of Output Data Large Display Panel for Output Probe.
- Post-processing and Inspection of Output Data Interface Output Data to Matlab.
- Reliable Saving of Simulation Data Save Probe Configuration and Data.



Figure 4.1: The ArtiSynth Timeline controlling a jaw motion simulation: (a) input probe (e.g. muscle activation), (b) output probe (e.g. incisor position), (c) play controls, (d) save / load buttons, (e) current time cursor. Input probe data can be modified globally by stretching and translating probes along the timeline or locally by directly dragging data knot points within the probe display.

4.1.2 ArtiSynth Timeline

The ArtiSynth Timeline integrates input data manipulation, simulation control, and output data extraction in an intuitive interface that is designed using the metaphor of a timeline typically used in video editing. Input data form "input probes" that drive the simulation while output data is viewed by "output probes". Figure 4.1 shows the ArtiSynth Timeline in use during a jaw motion simulation.

In order for the Timeline to be used for simulation control, the jaw model was instrumented with a complete set of input and output probes: input activation levels for muscles and muscle groups, and output positions, velocities, and forces.

4.1.3 Input Controls

The input probe framework provides a mechanism for applying time varying data to parameters within the jaw model. The main time-varying input parameters for dynamic simulation are muscle activation levels. We have instrumented the jaw model with input probes for muscle drive trajectories. These probes can be loaded with default data files, including step, ramp, and pulse curves, or with arbitrary data, such as recorded muscle activity. Input probe data is interpolated (step, linear, cubic) for the integration timestep of the simulation. Input data is manipulated by stretching, cropping, or translating input probe blocks within the Timeline, and by scaling data amplitude or directly dragging knot points within the probe display.

In addition to time-varying muscle input, we have implemented controls

Chapter 4. Creating a Comprehensive Simulation Interface

for applying constant levels of muscle activation and combining multiple muscles into functional groups. Controlling constant levels of muscle activation is important for simulating muscle tone. Tone is low level DC offset muscle activation that is present in muscles of awake humans and is important for jaw rest posture maintenance [39]. The concept of muscle grouping is an important aspect of controlling jaw simulation, since there are a large number of individual muscles in the jaw model. Basic muscle grouping is achieved through probes that contain data for multiple muscles, such as the jaw openers group (Digastric, Mylohyoid, Geniohyoid, and Lateral Pterygoid muscles) and the jaw closers group (Temporalis, Masseter, and Medial Pterygoid muscles). Functional muscle grouping is achieved by specifying co-contraction groups, which are controlled by a single activation level. Both multi-muscle probes and co-contraction relationships are controllable from the GUI; this provides the user with the flexibility to control input muscles at varying levels of granularity.

4.1.4 Output Visualization

The output probe framework in ArtiSynth measures properties of the model during the simulation and displays that data within the Timeline. In addition to the small output display within the timeline a larger detailed plot can be viewed.

The jaw model has been instrumented with a number of default output probes that fall into two main classifications: model motion and model forces. Motion probes include 6 DOF body positions, 6 DOF body velocities, midincisor point position, and condyle positions. Force probes include total

muscle force, passive muscle force alone, TMJ forces, bite forces, and food bolus resistances.

We have also developed a process to interface output probe data to Matlab for data processing and detailed graphical plots. Output probe data from ArtiSynth can be saved in a text format that is readable by Matlab. Matlab scripts have been developed to generate position versus position traces of the mid-incisor point motion in different view planes (e.g. mid-sagittal plane), which is a common representation of jaw motion.

In addition to measured data on the timeline, ArtiSynth provides a graphical rendering of the model useful for visual inspection of body motion during simulation. We have added additional rendered object for model components such as constraint planes and food boluses, as well as important reference points, such as TMJ contacts, bite contacts, centre-of-mass points, points of rotation, and anatomical landmarks. Visibility of model components (meshes, muscles, constraints, tissues, boluses) is independently controlled. Additionally, the view of the model is controllable and can be set to fixed orthogonal views (front, top, right, et al.). Another useful model visualization is color changing of the muscles and boluses that denote their internal state during the simulation as described in section 3.3.

4.1.5 Jaw Properties Control Panel

During validation the jaw model properties are kept fixed in order to show that the model can simulate plausible motion for multiple differentiated tasks. However, a set of model parameters were made modifiable through the user interface to enable a researcher to study the effect of morphological changes

Integration Method	RungeKutta4			
Maximum Step Size	0.6010			
Skeleton: Visible	🗹 Edges 🗍 1	fransparent 🖸		
Tissue: Visible	E			
Muscles: Visible	g			
Constraint: Visible	র্থ			
JAW Floating	Ø			
RIGHTBOLUS: Diameter (nim)	5.0	Max Resistance (N)	100.0	isActive 🗹
LEFTBOLUS: Diameter (mm)	4.0	Max Resistance (N)	60.0	isActive []
Jaw Rot Damping	1089000.0	<u>(</u>)		
Jaw Trans Damping	403.00			
Head Angle	0.0000			
Digastric	0.308600			
Lat Pterygold	0.685200	@		
Med Pterygoid	0.530900			
Ant Temporalis	0.080200		*****	
Post Temporalis	0.111100	-0	-	
CondylarAngle	15.000			
rCondylarAngle	15.000	······································		
iCondylarCant	-5.000		ante-	
rCondylarCant	5.000			
IMedWallAngle	7.000			
rMedWallAngle	-7.000			
IPostWallAngle	0.000		-	
rPostWallAngle	0.000			
occlusalAngle	6.500	······································	-	

Chapter 4. Creating a Comprehensive Simulation Interface

Figure 4.2: One of the jaw model control panels that expose internal dynamic properties of the model to be modified by a researcher. This panel is used in the mastication simulation and provides control over the TMJ constraint morphology.

on simulations of jaw movement. Various control panel sets have been developed that group modifiable parameters appropriate for different simulations. A control panel for the mastication simulation is shown in Figure 4.2. The full set of controllable jaw parameters are as follows:

- Joint morphology: articular fossae forward angle, articular fossae lateral cant, medial wall angle, posterior wall angle
- Bite morphology: angle of occlusal plane for bite contacts

- Food Bolus: number of boluses, location, size, stiffness, viscosity, maximum resistance threshold
- Connective Tissue: stiffness, damping
- Fix bodies in space in order to isolate parts of the model for simulation
- Damping: general rigid-body translational and rotational damping
- Head rotation: static skull rotation about C1 vertebrae
- Passive muscle properties: force at max stretch, force-length profile (linear, exponential)
- Integration scheme be chosen from Forward Euler, Symplectic Euler, and 4th order Runge Kutta
- Maximum integration timestep

Currently rigid-body meshes and muscle attachment sites are not modifiable through the ArtiSynth GUI. These major structural changes are possible by loading new model geometry from Amira as described in section 3.2.3.

4.2 Contributions to the ArtiSynth Project

As the first dynamic, anatomical model developed in ArtiSynth, the jaw model has been instrumental in the system's design, implementation, and test. The development of model properties and data probes were motivated by the jaw model, and user feedback from performing jaw simulations was important for system testing and interface refinement.

4.2.1 Testing

The jaw model is the most fully featured ArtiSynth model created to date and exercises all major components of the software system. It has therefore, been instrumental in systematically testing ArtiSynth for correctness and completeness.

Building the jaw model tested the ArtiSynth MechModel API as it was used for rigid-bodies, dampers, and rendering. The jaw model also tested ability to extend basic MechModel components as was done for the muscle model. Much of the debugging effort has focused on the GUI components and ArtiSynth Timeline.

4.2.2 Development

Implementation of the jaw model has spawned development in ArtiSynth primarily with respect to model properties and probes. Model properties were extended to incorporate any numeric data type for the jaw model. Additionally, the process for loading and saving probe data and configuration was designed around the needs of the jaw model.

ArtiSynth probes have been extensively used in creating jaw simulations and we have implemented further functionality within the jaw model to permit probe grouping. Group grouping in the jaw model has motivated an extension to the core ArtiSynth data probe framework. The original probe framework provided a simple mechanism to apply data directly to and measure data directly from model properties. The extension to functional probes allows for more general mappings between the data and the model. Concepts

that are a direct result of the requirements of the jaw model include:

- Probe Fanout: one data stream can feed a number of input probes e.g. co-contraction of a group of muscles
- Input Data Manipulation: data streams are mathematically manipulated before being applied to the model e.g. muscle excitation that is a function of desired jaw stiffness
- Output Data Manipulation: raw output data from the model can be manipulated and combined to form more meaningful output graphs e.g. changing the units of an output data stream

The functional probe framework is currently being developed along with a graphical interface to allow probes to be built and connected with arbitrary mathematical equations and connected to model inputs and outputs.

4.3 Summary

This chapter has discussed the ArtiSynth Timeline and our efforts to create a comprehensive user-interface for jaw motion simulation. The interface supports manipulating input data, model parameters, simulation time progression, and output displays. Through the development and use of our simulation interface by an expert researcher we have made contributions to ArtiSynth in system testing and motivating new development.

Chapter 5

Simulating Jaw and Laryngeal Motion

The two previous chapters have discussed the construction of the jaw model and simulation interface. This comprehensive jaw simulation toolset must be validated to show that it is representative of a generic human with average structural and dynamic properties. In this chapter we illustrate that our model is representative of the human jaw and laryngeal system.

We report a number of relevant jaw motion simulations, using published values for putative muscle drive as discussed in section 2.3.5, in order to demonstrate the capability for our model to emulate a range of normal human function. These functions include jaw border movement (rest posture, maximum forward protrusion, and maximum opening), as well as the feeding motions of mastication and swallowing. Mastication is the most complex functional task simulated and we discuss it in further detail with respect to additional model requirements, input muscle patterning, and output incisor and condylar motion. We follow our simulation results with a discussion of our validation approach in light of the difficulties of subject-specific modeling. The chapter concludes with a description of a kinematic jaw model that we also investigate to incorporate recorded jaw motion into our simulations.

5.1 Validation Simulations

In this section we report the results of numerous jaw and laryngeal motion simulations generated with our toolset. Each simulation on its own illustrates plausible behaviour of our model and, taken on a whole, the set of simulations demonstrates the our model is representative of the physical system.

We begin with a discussion of our simulation methodology that describes our validation approach for our mixed-data model. We then describe the simulations showing appropriate ranges of jaw motion consistent with previously published models. This is followed by a more advanced simulation of human feeding function: swallowing and mastication. The mastication simulation is described in detail due to the additional modeling difficulties and because it is a significant research result.

5.1.1 Methodology

Our model is representative of a generic, average-valued human with structural characteristics of an individual person. The average and approximate values used for dynamic parameters in the model prevent it from being validated against recordings from a specific subject. Instead we use putative muscle drive and compare the model output against average-valued motion data from literature.

Our assumption is that a generic model of the human jaw system should be able to attain a range of normal human functional tasks without changing the underlying dynamic properties of the model. These are the criteria we have used to validate our generic model of the human jaw and laryngeal system.

To validate our model we chose to simulate a range of tasks with the same model. The simulations were chosen for consistency with validation criteria of previously published models and for their significance in dentistry. The simulations of rest, protrusion, and wide opening have simple muscle input signals that require constant contraction of known muscle groups. The swallowing and mastication simulations are time varying motions and require more sophisticated muscle contraction patterns. We use published values for timing and amplitude of muscle contractions to generate these simulations. For each task, the simulation output is compared with average-valued, published records of jaw and laryngeal motion. The studies we rely upon for muscle activation and body motion data are discussed in section 2.3.5.

5.1.2 Range of Jaw Motion: Rest, Protrusion, Opening

Three significant points of jaw border movement are mid-incisor point position at rest, at maximum forward protrusion, and at maximum opening. Rest posture and forward protrusion can be accurately simulated by the jaw system in isolation, while maximum wide jaw opening simulation requires the integrated jaw and laryngeal system.

Postural Rest

The postural rest task is designed to show the effect of gravity acting against passive tension in the mandibular muscles causing a small amount of jaw opening. The normal human range of interincisal separation in an upright person at rest and awake is 3-5 mm.



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Figure 5.1: Simulation output for the protrusion task: (a) plots of mid-incisor point displacement and force in the inferior head of the lateral pterygoid muscle, (b) trace of mid-incisor position in the mid-sagittal plane from clench to rest position and from rest position to maximum forward protrusion.

In order to achieve a plausible interincisal separation under gravity, our model required a steady-state activity of 0.04% maximum activation in the closer muscles (temporalis, masseter, and medial pterygoid). This low level activation is termed "muscle tone" and its required amplitude in our model agrees closely with similar findings in [39]. Increased activation of the closer muscles moved the mandible upward until it stopped rigidly at dental intercuspal contact.

Forward Protrusion

We simulated forward mid-line protrusion of the mandible by activating the inferior lateral pterygoid muscles alone. At maximal protrusion the jaw elevated slightly due to passive tension in the anterior temporalis muscles. The
model achieved a self-limited forward protrusion of 10 mm consistent with the normal range of jaw motion. Figure 5.1 shows the force and displacement plots for the protrusion task and a incisor position trace of close, rest, and maximal protrusion.



Figure 5.2: Simulation output for the opening tasks: (a) plots of mid-incisor point displacement and force in the opener muscles for opening with 0° head rotation, (b) trace of mid-incisor position in the mid-sagittal plane for jaw motion during opening with 0° head rotation and 15° head rotation cases.

Wide Opening

In addition to rest position and forward protrusion maximum, jaw opening is a significant end-point in jaw border movement, as shown in Figure 2.18. Accurate simulation of wide jaw opening requires mobility of the hyoid. This is discussed in previous studies on laryngeal motion (refer to section 2.3.5). Opening is a combined motion of downward rotation and forward translation of the mandible as well as laryngeal depression. The downward displacement

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Figure 5.3: The jaw model at 50 mm maximum gape, showing alignment of hyoid bone with lower edge of mandible during opening simulation.

and stabilization of the laryngeal complex was achieved by depressor muscles working against the upward pull of the jaw openers. The hyoid is the insertion site for the anterior digastric muscle, which is a primary jaw opener, and depression of the hyoid increases the muscle's mechanical advantage at extreme wide gape.

Our model was driven to maximum jaw opening by full activation of the jaw opening muscles (anterior digastric, mylohyoid, and inferior lateral pterygoid) as well as activation of the hyoid depressor muscles (sternohyoid, thyrohyoid, and omohyoid) to stabilize and slightly lower (1 mm) the laryngeal complex. Two simulations were performed and are diagrammed in Figure 5.2. For comparison to [62] we used reduced passive muscle tension characteristics for the closers and achieved a maximum gape of 38 mm. For comparison to [34] we applied a 15° rotation to the head, and the model achieved a full wide gape opening of 50 mm. At wide gape, with a backward rotated head, the anterior tip of the hyoid body was aligned with the lower edge of the mandible, which is consistent with cephalometric measurements published in [52]. The jaw model at 50 mm wide gape is pictured in Figure 5.3.

5.1.3 Laryngeal Motion: Swallow

The two main functions of human feeding are mastication and swallowing. By integrating laryngeal structures in our jaw model we have the initial capability to simulate swallowing. Although the tongue also plays a major role in swallowing, and it is not included in our model, the jaw and larynx alone can be used to analyze the interaction of suprahyoid and infrahyoid muscles in achieving stabilized laryngeal elevation. Swallowing is an important action to model because it requires a large range of laryngeal mobility. During swallowing, the laryngeal complex is displaced upward and forward in a quick active motion. The displacement is sustained during bolus transport. The complex then slowly returns to rest position under passive forces.

We initiated swallowing by activating the temporalis, masseter, and medial pterygoid muscles to elevate and stabilize the mandible. Upward motion of the larynx occurred following excitation of the digastric, mylohyoid, geniohyoid, and stylohyoid muscles.

Predicted magnitude and duration of upward and forward translation of the laryngeal complex is consistent with previous literature on laryngeal



Figure 5.4: Time-lapsed images of laryngeal complex elevation during simulated swallow.

elevation. Our model achieved a maximum hyoid elevation of 16 mm, which was held for 233 ms. At maximal elevation the hyoid bone aligned with the lower border of the mandible as shown in Figure 5.4.

Advanced study of the human swallowing motion requires an integrated tongue model and realistic soft tissue, as discussed in section 6.2, in order to better simulate the inertial and elastic properties of the larynx. This will enable the analysis of realistic muscle drive amplitudes in the sub-mandibular muscles during swallowing.

5.1.4 Advanced Simulation: Mastication

Mastication is the primary function of the human jaw system and the precursor to swallowing during feeding. The challenges of simulating chewing with a dynamic model are such that it has only been reported in one previous study [39]. Our goal was to generate a definitive chewing cycle with our model, using putative muscle activation timings from literature [49], that illustrates consistency with 6 degree-of-freedom recordings of mastication.

Simulation Challenges

Mastication simulation was chosen because it imposes additional significant requirements on the model over other functional tasks. The cycle starts with asymmetric opening. The passive tensions of the closer muscles are dynamically used in the turn-around point, and the closer muscles are highly activated during closing and tooth contact. This motion engages the large jaw closing muscles and generates large forces for the muscles, joints, and bite contact. The simulation includes the addition of dynamic food bolus elements that provide a varying resistance to the closing jaw before tooth contact and simulates food disintegration at tooth contact. Unlike wide jaw opening that has a defined start and end position, the cycle is a continuous dynamic action that has specific timing requirements.

All of these factors combine to make mastication a much more difficult simulation than free jaw motions. Furthermore, mastication simulation is a good measure of validation as we use the same static model parameters for mastication simulation as are used in the other motion simulations discussed above.

Constrained Joint

Initial simulations of free jaw motion used a simple planar constraint for the TMJ and garnered results that are consistent with previously published models. The single planar constraint became unstable under the large loads incurred in our first attempts at the chewing simulation. The working side condyle would quickly move laterally along the frictionless plane out of the normal joint region during the closing phase of the cycle, which would cause

the system to become unstable. Previous jaw models included ligaments and spring-like elements to provide posterior and lateral resistance to stabilize the TMJ model. The physical morphology of the articular fossae is concave in shape and provides lateral stabilization that would prevent the unrealistic condyle motion we found in simulating mastication with a single planar constraint.

In order to approximate the 3D shape of the articular fossae we added additional planar constraints for the medial wall and posterior wall that provide further guidance to the condyle. This joint model is analogous to the constraints provided by a typical semi-adjustable dental articulator as described in section 2.2.1. As in a mechanical articulator, all of the constraint angles of our joint model are modifiable and can be used to approximate subject specific joint morphology.

Muscle Patterning

We employed a researcher with over thirty years of jaw mechanics expertise to use our simulation-interface to create a mastication simulation with our model. The muscle contraction patterns used as input for simulation of the chewing cycle are based on published data on timing and amplitude from recorded electromyography reported by Moller [49], Hannam and Wood [26], and Wood et al. [83]. Starting from these average putative muscle drive patterns the input activation trajectories were minimally tuned by a expertresearcher to achieve a refined output incisor-point mastication envelope. The final muscle activations that achieved realistic mastication for our model are shown in Figure 5.5.



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Figure 5.5: Input muscle activation signals applied to our model for the definitive chewing simulation. Muscle abbreviations used are as follows: Posterior / Medial / Anterior Temporalis (PT / MT / AT), Superficial / Deep Masseter (SM / DM), Medial Pterygoid (MP), Inferior / Superior Lateral Pterygoid (ILP, SLP), and Digastric (AD).

Results

After a short duration of refining (10 hours), the jaw motion was compared with published data on jaw chewing motion. The lateral and frontal view of mid-incisor point motion closely agree with the Ahlgren chewing cycle envelope [1] and are shown in Figure 5.6. Our chewing cycle simulation also shows realistic timing for reciprocal condyle motion as shown in Figure 5.7.

We are currently building upon the definitive chewing cycle and using

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the model to examine the sensitivity of the chewing cycle to changes in structural morphology including joint shape, muscle placement, and occlusal plane orientation.



Figure 5.6: Trace of mid-incisor position for our simulation of a definitive chewing cycle: (a) frontal plane, (b) mid-sagittal plane.



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Figure 5.7: Time-varying displacement of the working-side and balancingside condyles during a simulated chewing cycle showing the balancing-side moving backward and seating in the articular fossa after the working-side.

5.2 Validation Discussion

In this section we have presented a validation study for our infra-mandibular model of a generic, average human. We rely on mean published values for normal human function in order to assess whether or not our average-valued human model is simulating normative and plausible motion. Additionally, the ability for our model to perform a wide range of functional tasks validates that the model has captured the constituent dynamics of the jaw system.

We do not have an exact replica of a specific person; the structure of the model is based on CT image data from an individual, but much of the underlying dynamical model consists of published average values. Therefore, it would not be appropriate to attempt to validate our model against recorded data from a specific individual.

Our model could be extended to include more subject specific properties and made more representative of an individual. This would require the integration of additional data into the model, such as muscle attachment locations and muscle cross-sectional sizes, provided such data could be determined by experiment. Additionally, it is unlikely that it will ever be possible to derive individually-matched data for muscle parameters such as length-tension and velocity-tension for all of the human jaw muscles. Subjectspecific validation would require extensive data collection including EMG recordings matched with accurate jaw motion tracking for multiple actions. Records of 3D bite force and jaw stiffness would also be useful, but are difficult to record without affecting the subject's motion task. The difficulties of subject-specific model validation through comparison with a full complement of data recording remain a significant impediment to the practical application of such validation schemes.

Adaptation of a generic model to match salient characteristics of a specific subject is perhaps a more practical method for modeling an individual. Model adaptation is a planned feature for the ArtiSynth modeling software and may be used to adapt the jaw model to specific individuals or classes of individuals. However, our current generic model has significant potential as a research tool in analysis of biomechanics in the norm. As well, arbitrary morphological modification is possible with our modeling toolset and can be used to model and compare specific medical disorders.

Our validation simulations use average jaw motion as functional goals; however, addition modeling and simulation research may require the inte-

gration of subject-specific jaw motion records. In the following section, we report our initial efforts at developing a kinematic jaw model that has been used to generate animations of recorded jaw motion. The integration of kinematic data is useful for advanced simulations and muscle pattern prediction research using our with our dynamic jaw model.

5.3 Kinematic Simulations

In addition to muscle-activated forward simulations with the dynamic jaw model, we have also developed a data-driven kinematic jaw model for animating recorded jaw motion. 6 DOF position data recorded with an NDI Optotrak system [54] is used to move the geometry of the dynamic jaw model. Basic pre-processing scaling is applied to target recorded data to the model and more sophisticated pre-processing techniques are planned. A picture of the kinematic jaw model and recorded motion data imported on the timeline is shown in Figure 5.8.

This kinematic model is significant for the ArtiSynth project because it is the first model with a direct interface to recorded simulation data. In dentistry it is common to record 6 DOF jaw movement in normal and abnormal subjects. Additionally, data-driven (parametric) modeling is widely used in the speech community for which ArtiSynth is targeted.

The kinematic model is also significant for our dynamic jaw modeling efforts because it enables recorded motion data to be incorporated into dynamic simulations. Our future research directions include schemes for controlling jaw simulations through automatic muscle pattern prediction and require

kinematic input data as target trajectories for jaw motion (see future work section 6.2.3).



Figure 5.8: The kinematic jaw model showing input data source on large Timeline display window.

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5.4 Summary

In this chapter we have presented the results of forward simulations of jaw motion consistent with published literature to show that our model is a realistic representation of the anatomical system. The results of advanced simulations of the human chewing cycle, compared with records of mastication motion, have been presented and are summarized in Table 5.1 below. A kinematically-driven jaw model has been developed as an extension to our dynamic jaw model in order to integrate recorded kinematic in future simulation efforts.

Task	Incisor	Hyoid	Time	Active Muscles	
	Disp	Disp			
Rest Posture	5 mm			none	
Protrusion	10 mm	<u> </u>		ILP, SLP	
Opening	50 mm	-1 mm		DG, ILP, SLP	
Swallowing	0 mm	16 mm	233 ms	Elevation: DG, MH, GH	
				Stabilization: OH, SH, ST	
Mastication	gape 23 mm		550 ms	All Muscles - see Fig 5.5	
	lateral 5 mm				

Table 5.1: Jaw motion results for the complete set of functional tasks simulated. Muscle abbreviations used are as follows: Inferior / Superior Lateral Pterygoid (ILP / SLP), Digastric (DG), Mylohyoid (MH), Geniohyoid (GH), Omohyoid (OH), Sternohyoid (SH), Sternohyroid (ST).

Chapter 6

Conclusions & Future Work

We have described the development and validation of a dynamic jaw modeling system designed for studying biomechanics of jaw motion. In this chapter we conclude the thesis by summarizing our contributions and delineating future directions of our work. We begin by highlight contributions made in our model development, interface design, and simulation results. We will then discuss planned future research that includes refining and extending our model as well as performing further analysis of jaw biomechanics using our modeling toolset. The chapter ends with some brief concluding remarks.

6.1 Contribution Summary

Our modeling efforts are summarized by highlighting three main contributions: dynamic jaw modeling advancements, the development of a fullyfeatured graphical simulation interface, and the results of simulations performed with our toolset.

Model: We have advanced the art of dynamic jaw modeling by integrating laryngeal anatomy into our jaw model and by incorporating CT data to inform model geometry. These features extend the utility of the model providing the capability to simulate combined jaw and laryngeal function and import subject-specific data.

Interface: We have created a usable toolset by developing a graphical interface for our model through a process of user-centered design. The Control Panel interface provides access to all internal model properties, while the Timeline integrates input data manipulation, simulation controls, and output displays into a unified interface.

Simulations: We have proposed a validation approach for our averagevalued model postulating that a dynamic model is representative of an anatomical system if it can achieve plausible motion for a wide range of function with constant model parameters and putative inputs. We report simulation results for maximum range of jaw motion, primitive swallowing action, and a definitive mastication cycle demonstrating behaviour consistent with published records of muscle drive and motion in normal jaw and laryngeal function.

6.2 Future Work

There are numerous avenues of research that spawn from our efforts presented in this thesis. The future work can be classified into refinement of the existing model, extension of the model to include more anatomical components, and additional utilization of the modeling toolset for simulation of jaw and laryngeal biomechanics.

6.2.1 Enhanced Model Components

Larynx Soft Tissue: The current mass-spring tissue elements are a rudimentary approximation of the soft connective tissue of the larynx. Replacing these tissue elements with volumetric Finite-Element meshes would improve the accuracy of the tissue shape, connection area, and mechanical properties. FEM meshes are a base component in ArtiSynth so their incorporation into the jaw model is immediately possible.

Curvilinear TMJ: The condylar guidance of the articular eminentia and fossae would be more accurately represented by a 3D curvilinear constraint surface. A curvilinear surface is an extension of the planar constraint with the surface normal being a function of the contact point location. The derivative of the normal with respect to contact point location would also be required for implementation of the constraint. A curvilinear joint could be compared with the current multi-planar TMJ model to determine its effect on the mechanics of the jaw simulations already performed.

Accurate Teeth Contact: ArtiSynth has facilities for mesh-to-mesh collision detection and contact. This could be used with the model's current high resolution teeth meshes to perform advanced simulations of tooth contact. The advantage of full collision detection is that the bite constraints could include tooth facet interactions and friction during tooth grinding (bruxism), static clench, and chewing.

6.2.2 Additional Connected Anatomy

Deformable Tongue Model: We are also developing a muscle driven finite-element tongue model [80] and we are working toward dynamically interconnecting it with the rigid-body jaw-larynx model. Our preliminary model integration has a rudimentary implementation of this connection and is pictured in Figure 6.1. This is an extremely rich direction for biomechanics modeling as the tongue body and extrinsic muscles have a significant effect on laryngeal positioning, and the jaw-tongue-larynx system captures the predominant volitional contributors to the fundamental human functions of feeding and speaking.



Figure 6.1: Initial results of integrating a deformable tongue model with our jaw model.

Facial and Pharyngeal Tissue: Simple contractile FEM shells could be included that represent lips, cheeks, soft palate, epiglottis, and pharynx. In combination with the tongue model this would create an enclosed oral cavity and provide the constituent anatomical elements required to simulate bolus transport to the esophagus during swallowing.

6.2.3 Advanced Simulations

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Muscle Pattern Prediction: As stated in [30], the prediction of muscle recruitment patterns for the human mastication system is the dominant challenge in jaw movement analysis. We are working on an inverse-dynamics scheme to automatically drive the jaw model to follow a desired motion trajectory for speech and mastication tasks. Parameters of muscle force magnitude, jaw stiffness, and task speed are being studied to solve the actuator redundancy problem.

Chewing and Swallowing: The current model has been used to examine mastication. With the addition of a tongue model the system can be made to simulate the complete feeding action: chewing cycle, food bolus disintegration, and bolus transport. Possible research topics for simulating swallowing would be to study forms of dysphagia (disorders of swallowing). This could be done with either structural changes to the anatomy of the model or by arbitrary changes to muscle input drive to simulate problems such as paralysis, dyskinesias, and other dysfunctional conditions in the craniomandibular and orofacial regions.

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6.3 Conclusions

We have presented the development a comprehensive modeling toolset for studying jaw and laryngeal biomechanics. Our dynamic model is representative of the entire infra-mandibular skeleton, derived from image data, modifiable, and extensible. We have developed the interface required by researchers to simulate jaw and laryngeal motion using our model. We have presented preliminary results of jaw motion simulations that agree with the validation studies performed in previously published literature.

The project is open-source and lends itself to further advancement and extension to study specific components and disorders associated with the mechanics of the jaw and larynx. We are currently integrating our model with a deformable tongue model to create a complete, dynamically connected jaw-hyoid-tongue system. The scientific applications of this computational model are numerous and provide many paths of future research opportunity.

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Appendix A

Jaw Model Properties

A.1 Model Data Sources

Model Component	Data Source		
Cranium Mesh	Morphed Generic Mesh		
Maxilla Mesh	CT Data		
Mandible Mesh	CT Data		
Hyoid Mesh	CT Data		
Thyroid Mesh	Morphed Generic Mesh		
Cricoid Mesh	Morphed Generic Mesh		
Arytenoid Meshes	Morphed Generic Mesh		
Tooth Crown Meshes	Generic Mesh		
Teeth Locations	CT Data		
Muscle / Tissue Attachments	Average Values [70]		
Muscle Lengths	CT Data		
Muscle Force Properties	Average Values [78]		
Joint Constraint Angles	Average Values [70]		
Larynx Tissue Stiffness	Arbitrary		

Table A.1: Data sources for various model components and subcomponents.

A.2 Body Mass and Inertia Values

Body	Mass (g)	\mathbf{I}_{xx}	\mathbf{I}_{yy}	\mathbf{I}_{zz}
		(kg/m^2)	(kg/m^2)	(kg/m^2)
Mandible	20.0	182.200	92.190	125.200
Hyoid	1.0	2.154	1.611	7.432
Thyroid-Cricoid	4.7	2.154	1.611	7.432

Table A.2: Inertia properties for the dynamic rigid-body structures of the jaw model.

A.3 Mandibular Muscle Properties

Muscle	Rest	Max	Tendon-	Cross-	Max	Max
Group	Length	Length	Fibre	sectional	Active	Passive
	(mm)	(mm)	Ratio	Area	Force	Force
				(mm^2)	(N)	(N)
SM	49.17	63.91	0.46	4.76	190.40	2.86
DM	31.06	47.92	0.29	2.04	81.60	1.22
AT	90.35	114.73	0.50	3.95	158.00	2.37
MT	81.51	115.63	0.48	2.39	95.60	1.43
PT	63.80	83.63	0.51	1.89	75.60	1.13
MP	50.77	63.45	0.64	4.37	174.80	2.62
AD	40.14	51.58	0.00	1.25	50.00	0.75
SLP	21.10	28.72	0.00	1.25	50.00	0.75
ILP	32.37	42.64	0.00	1.25	50.00	0.75

Table A.3: Dynamic properties of the mandibular muscles: Superficial Masseter (SM), Deep Masseter (DM), Anterior Temporalis (AT), Medial Temporalis (MT), Posterior Temporalis (PT), Medial Pterygoid (MP), Digastric (DG), Superior Head of the Lateral Pterygoid (SLP), Inferior Head of the Lateral Pterygoid (ILP).

Appendix B

Supplemental Information

B.1 RK3 Integration Scheme

The 3rd order Runge Kutta numerical integration scheme is given as [9]:

$$\begin{aligned} \tilde{x}_{n+1} &= x_n + \Delta t \ v(x_n, t_n) \\ \tilde{x}_{n+2} &= \tilde{x}_{n+1} + \Delta t \ v(\tilde{x}_{n+1}, t_{n+1}) \\ \tilde{x}_{n+1/2} &= \frac{3}{4} x_n + \frac{1}{4} \tilde{x}_{n+2} \\ \tilde{x}_{n+3/2} &= \tilde{x}_{n+1/2} + \Delta t \ v(\tilde{x}_{n+1/2}, t_{n+1/2}) \\ x_{n+1} &= \frac{1}{3} x_n + \frac{2}{3} \tilde{x}_{n+3/2} \end{aligned}$$

B.2 Planar Constraint Example

In this section we provide a numerical example of the constraint formulation used in jaw model. For this example we will use a rigid block as the constrained body and a plane located at the origin as the constraint.



Figure B.1: A schematic of the planar constraint example: a block hanging at rest as its upper corner is constrained to the planar surface.

Block Dimensions:

$$lx = 100.0$$
$$ly = 80.0$$
$$lz = 70.0$$

where lx, ly, and lz are the length, width, and height of the block respectively.

Block Dynamic Properties:

where m is the mass, com is the centre of mass point, J is the rotational inertia, and M is the full 6×6 spatial inertia matrix in the body-frame.

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Constraint Properties:

$${}^{W}n = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^{T}$$

 ${}^{B}P = \begin{bmatrix} 50.0 & 40.0 & 35.0 \end{bmatrix}^{T}$

where ${}^{W}n$ is the normal vector in world-frame specifying the planar constraint normal direction and ${}^{B}P$ is the vector in body-frame specifying the upper corner point on the block that is constrained.

Example Pose:

We start with a planar constraint surface located at the origin and the block with its upper corner constrained to remain in contact with the surface. The block falls below the plane and comes to rest as shown in Figure B.1. At this time the centre of mass of the block is directly below the contact point. The the rigid transformation specifying the pose of the block in world-frame is given by:

$$R_{BW} = \begin{bmatrix} 0.639 & -0.114 & -0.769 \\ -0.367 & 0.829 & -0.423 \\ 0.685 & 0.548 & 0.480 \end{bmatrix}$$
$$P_{BW} = \begin{bmatrix} 0.0 \\ 40.0 \\ 73.0 \end{bmatrix}$$
$$X_{BW} = \begin{bmatrix} R_{3\times3} & P_{1\times3} \\ 0_{3\times1} & 1 \end{bmatrix}$$

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$$X_{BW} = \begin{bmatrix} 0.639 & -0.114 & -0.769 & 0.0 \\ -0.367 & 0.829 & -0.423 & 40.0 \\ 0.685 & 0.548 & 0.480 & 73.0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where R_{BW} , P_{BW} , and X_{BW} are the rotation, displacement and rigid-transform between the world-frame and body-frame respectively.

The only external force on the body is that applied by gravity, which yields 6D applied force and torque wrench on the block follows:

$${}^{W}F_{a} = \begin{bmatrix} 0 & 0 & -9800 & 0 & 0 \end{bmatrix}^{T}$$
$${}^{B}F_{a} = \begin{bmatrix} -6714.9 & -5371.9 & -4700.39 & 0 & 0 \end{bmatrix}^{T}$$

where ${}^{W}F_{a}$, ${}^{B}F_{a}$, and X_{BW} are the external applied force wrenches on the body represented in world-frame and body-frame respectively.

The constraint plane is specified by a single constraint wrench represented in world-frame and body-frame as follows:

$${}^{W}G = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$
$${}^{B}G = \begin{bmatrix} 0.69 & 0.55 & 0.48 & 0 & 0 \end{bmatrix}$$

We compute the required reaction force at the contact point with the

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constraint projection equation (equation 3.3):

$$F_{c} = -G^{T}(GM^{-1}G^{T})^{-1}GM^{-1}F_{a}$$

The spatial inertia matrix for the block, M, is symmetric and thus easy to invert:

$$M^{-1} = \begin{bmatrix} 1.0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{941.7} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{1241.7} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{1366.7} \end{bmatrix}$$

Using all terms represented in body-frame $({}^{B}F_{a}, {}^{B}G, \text{ and } M^{-1})$ we solve the above equation to find:

$${}^{B}F_{c} = \begin{bmatrix} 6714.9 & 5371.9 & 4700.39 & 0 & 0 \end{bmatrix}^{T}$$
$${}^{W}F_{c} = \begin{bmatrix} 0 & 0 & 9800.0 & 0 & 0 \end{bmatrix}^{T}$$

The constraint applies a reaction force normal to the constraint plane at the contact point that exactly opposes the force of gravity, thus keeping the constrained corner of the block corner in contact with the plane surface.