Biomechanical Modeling with ArtiSynth
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www.artisynth.org
Outline

- Modeling oral anatomy
- Overview and demo of ArtiSynth
- Jaw-hyoid model
- Tongue model
- Project directions and opportunities

Modeling Oral Anatomy

- Mastication
- Swallowing
- Speech
- Breathing

Biomechanics
\[ F = ma \]
Motivation

Understanding Physiology

• Biomechanical models relate anatomical structure to dynamical function

• Study neuromotor control problem
  – Use model as platform to test hypotheses
  – How much of function is actively controlled?

Motivation

Clinical Application

Medical Disorders
  – Dysphagia (stroke-induced)
  – Post Surgical Deficits
  – Obstructive Sleep Apnea
  – Speech Pathology

• Further understanding of dysfunction
• Develop and simulate possible treatments
ArtiSynth
Modeling Software

What is ArtiSynth?

• Java-based API for model creation
• GUI support for interactive editing, simulation, and observation

Open Source
Research Oriented
Collaborative
Need to Simulate and Connect various Anatomical Components

Mechanical Model
Building Blocks

Particles
Rigid bodies
Deformable bodies (FEM)
Springs
Muscles
Constraints
Component Hierarchy

All Instances of a General Second Order Mechanical System

\[ M(x) \ddot{x} = f(x, \dot{x}, t) \]

Fundamental Dynamic components:

- \textit{particles} (3 DOF)
- \textit{rigid bodies} (6 DOF)
- \textit{reduced coordinate models} (future)
Solving the Mechanical System

\[ M(x) \ddot{x} = f(x, \dot{x}, t) \]

\[ \dot{x} = \int_0^t \ddot{x} \, dt = \int_0^t M^{-1} f(x, \dot{x}, t), \]

\[ x = \int_0^t \dot{x} \, dt \]

Numerical Solution

Simplest method: explicit forward Euler

\[ \ddot{x}^{i+1} = \ddot{x}^i + h \dddot{x}^i \]

\[ = \ddot{x}^i + h M^{-1} f^i(x, \dot{x}, t) \]

But often unstable; need implicit methods:

\[ \ddot{x}^{i+1} = \ddot{x}^i + h M^{-1} f^{i+1}(x, \dot{x}, t) \]
Implicit Solution

Approximating $f^{i+1}$ as

$$f^{i+1} \approx f^{i}(x^{i}, \dot{x}^{i}, t^{i+1}) + \frac{\partial f}{\partial x} \Delta x + \frac{\partial f}{\partial \dot{x}} \Delta \dot{x}$$

leads to

$$\left( M - h \frac{\partial f}{\partial \dot{x}} - h^{2} \frac{\partial^{2} f}{\partial x^{2}} \right) \ddot{x}^{i+1} = \left( M - h \frac{\partial f}{\partial \dot{x}} \right) \ddot{x}^{i} + h f^{i}$$

Matrix is large, sparse, and usually SPD

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Finite-Element Models

Deformable Solids

- Lumped Mass
- 3D Quasi-Linear Elements
- Fast Simulation Techniques
FEM Stiffness Warping

[Müler and Gross 2004]

Corrects distortion in small deformation (Cauchy strain) FEMs by factoring out global rotations

Muscle Activated FEMs

Muscle forces are applied between selected node pairs

\[ f_{ij} = \alpha_{ij} u_{ij} \]

\[ u_{ij} = \frac{x_j - x_i}{\|x_j - x_i\|} \]
Rigid body collisions handled by applying impulses

FEM collisions handled by projection of penetrating nodes
Component Properties

Exposed component attributes that can be read or set by external agents

Particle

{name, mass, externalForce, renderProps}

Graphical Interface for Model Manipulation

Transformer

Timeline

Control Panel
Model Components

- Rigid-bodies
- Constraints
- Muscles
- Tissue

Vertebrae
Maxilla
Mandible
Hyoid
Thyroid
Cranium
Cricoid

Model Components

Cranium
Maxilla
Mandible
Hyoid
Thyroid
Cricoid

Vertebrae
Rigid-bodies
Constraints
Muscles
Tissue

Temporomandibular Joints (TMJ)
Tooth Contact
Cricothyroid Joint

Closer Muscles
Infrahyoid Muscles
Opener Muscles

Infrahyoid Muscles
Model Components

Rigid-bodies
Constraints
Muscles
Tissue

Rigidbody Damping
Hyothyroid Membrane
Cricotracheal Membrane

Model Components

Rigid-bodies
Constraints
Muscles
Tissue

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Advancements

• Integrated Larynx

• Model geometry from CT data

CT Data

High-resolution cone-beam CT imaging
- High-Resolution: 0.4 mm³
- Range: lower orbit to cricoid bone
CT Data Extraction

Manual processing with Commercial Software Tools:
- Amira: image processing
- Rhino: mesh manipulation

- Noisy Segmented Data (Amira)
- Morphed Generic Mesh (Rhino)
- Constructed Fitted Mesh (Rhino)
- Muscle Attachment “Landmarks” (Amira)
- Mesh Registration (Amira)

Data Integration

- Skeleton Geometry: Meshes
- Important Locations: Landmarks
  - Muscle and Tissue Attachments
  - Anatomical Landmarks

- Amira
- ArtiSynth
Range of Motion

- Tested range of jaw motion for model:

![Graph showing range of motion](image)

Incisor position in sagittal plane

Laryngeal Motion

Primitive Swallow:
- Mandible braced in clench
- Suprathyroid muscles activated

Advanced swallow study:
- Integrated tongue model
- Larynx soft tissue

[Stavness et al. 2006 Springer LNCS #4072]
Chewing Simulation

Challenges:
- Lateral opening
- Moving Hyoid
- Large closer forces
- Food bolus

[Jaw & Hyoid Motion:
Right-sided Chew (10mm 14N bolus)]

- Consistent with Hiinemae & Palmer
Adaptation of ICP Tongue Model

ICP Tongue
- Accurate (ANSYS)
- Slow (600x realtime)

ArtiSynth Tongue
- Approximate (~linear)
- Fast (10x realtime)

Gerard et al., 2003
Vogt et al., 2006

Tongue Muscles
- Anterior, Middle & Posterior Genioglossus
- Superior & Inferior Longitudinalis
- Hyoglossus
- Transversalis
- Verticalis
- Mylohyoid
- Geniohyoid
- Styloglossus
Tongue Motion Simulation

Connection to Jaw Model

- Fully dynamic Jaw-Tongue-Hyoid model

- Research in progress:
  - simulate swallowing and paralysis disorders
  - hyoid depression in wide jaw opening
Connected Jaw-Tongue-Hyoid Model

Airway and Pharynx
*Collaboration with Art Miller (UCSF)*
Pharynx Constrictor Muscles

Geometry

Tongue-Airway Model
Project Directions

OPAL: upper-airway medical simulation
  – Patient-specific modeling
  – Chewing, swallowing, obstructive sleep apnea

Visual Voice: audio-visual speech
  – Singing synthesis for performance

Opportunities

• Undergraduate co-op / summer work terms
• Graduate students starting in 2008-09

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