Model-based estimation of muscle and joint forces based on inverse dynamics using the AnyBody Modeling System

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Program for today

- Introduction
- Lecture: Background of the AnyBody software
- Exercise: Getting Started with AnyScript
- Lecture: Muscle mechanics
- Demo: Mandible model
- Exercise: Analysis of the mandible model
- Lecture: Application Mandible model

Note!
It is a pretty big job to learn AnyBody in 2.5 hours.

Expect to use more time if you want to use this for projects.
AnyBody: The general idea

\[ \sum M = 0.30 \cdot 5 \cdot 9.81 - F_m \cdot 0.05 = 0 \]

\[ F_m = \frac{14.72}{0.05} = 294 \text{ N} \]

The same principle applies to more complex systems, except…
...we have too "many" muscles!

The same principle applies to more complex systems

• The mechanics is too complicated to do by hand.
  – 3-D
  – Many degrees of freedom
  – Closed chains
  – Contact conditions
• The muscle redundancy calls for an optimality criterion.
• We need software to handle the computational task.
Calculation of muscle force

What to do about this?

Inverse dynamics

- Movement and external forces are input into the model
- Statical indeterminacy: more muscles than degrees of freedom.

To analyze the human movement by inverse dynamics, we must find a solution to this problem.
**Muscle recruitment**

Minimize

\[ G(f^{(M)}) \]

Subject to

\[ \text{Cf} = \text{d} \]

\[ f_i^{(M)} \geq 0, \quad i \in \{1,\ldots,n^{(M)}\} \]

Objective function. Different choices give different muscle recruitment patterns.

Muscles cannot pull

Equilibrium equations

**Minimum fatigue formulation**

Minimize maximum relative muscle load or minimize fatigue or maximize endurance

Minimize

\[ \max\left(\frac{f_i^{(M)}}{N_i}\right), \quad i \in \{1,\ldots,n^{(M)}\} \]

Subject to

\[ \text{Cf} = \text{d} \]

\[ f_i^{(M)} \geq 0, \quad i \in \{1,\ldots,n^{(M)}\} \]

Muscle force

Muscle strength.
Message

- Ergonomics and medicine are going computational
- This is a change of paradigm
  - from empirical to analytical
  - from qualitative to quantitative

Computer-Aided Ergonomics in a nutshell

Shoulder joint forces
1. Wheelchair propulsion

Example thanks to Philip Requero, Los Amigos Rehab Center, California, USA

2. Egress

- Ageing population.
- Limited muscle strength.
- Arthritis in the knees.
- Investigation of handle position.
The Movement

Muscle effort

- High handle position preferable
- Near-standing positions less strenuous
Knee joint forces

The AnyBody Modeling System

- Software for modelling and analysis of the musculo-skeletal system

- Main features:
  - Based on inverse dynamics and optimisation principles
  - Built-in model definition language: AnyScript
  - Capable of handling models with hundreds of muscles on personal computers
Assumptions and limitations

• With AnyBody one can only model skilled movements

• Explosive movements cannot be modelled due to wobbling masses

Tutorial AnyBody: Getting Started with AnyScript

• Try to do the tutorial: Getting Started with AnyScript

• You have ca. 1.5 hour after that I will continue with a short lecture about muscle mechanics.
Muscles – types

- Non-striated muscles
  - Autonomic
  - Veines, intestine
- Striated muscles
  - Cardiac muscles
    - Autonomic
  - Skeletal muscles
    - Voluntary control
    - 50 % of body weight

Muscles – contraction types

- Concentric contraction
  - Muscle shortens
- Isometric contraction
  - Muscle keeps the same length
- Eccentric contraction
  - Muscle lengthens
Single muscle fiber

Cross-bridge theory (Huxley)
Cross-bridge theory (Huxley)

(a) Relaxed state

(b) Contracted state

Modeling muscle geometry in AnyBody

What are the differences?
Elements of a modeled muscle

- Kinematics: The origin-insertion path

- Strength
  - Dependent on physiological properties
  - Depending on operating state

The origin-insertion path in AnyBody

- Straight line

- Via point muscles
  - The muscle passes through via points like a thread through the eye of a needle (tibialis anterior)

- Wrapping muscles
  - This means that the contact forces between the bone and the muscle are always perpendicular to the bone surface, and the muscle may in fact release the contact with the bone and resume the contact later depending on the movement of the body
Minimum fatigue formulation

Minimize maximum relative muscle load or minimize fatigue or maximize endurance

Minimize

\[ \max \left( \frac{f_i^{(M)}}{N_i} \right), \quad i \in \{1, \ldots, n^{(M)}\} \]

Subject to

\[ \text{Cf} = \text{d} \]

\[ f_i^{(M)} \geq 0, \quad i \in \{1, \ldots, n^{(M)}\} \]

Muscle strength depends on:

- The amount of fibres parallel with each other i.e. Cross-sectional area
- The neural drive
- Length
- Shortening /lengthening velocity
A.V. Hill (1886-1977)

- Nobel prize in 1922
- Muscle mechanics
- Muscle energetics

Hill Muscle Model (1)

- CE = Contractile Element
- SEE = Series Elastic Element
- PEE = Parallel Elastic Element
Hill Muscle Model (2)

Demo mandible model
(Monkey see – Monkey do)
Exercise Mandible model

1. Download Mandible.zip from:
   http://www.smi.hst.aau.dk/~mdz/Download/Mandible.zip

2. Calculate the joint reaction forces for the given clenching force. Write down the maximal values for both sides. Look also at the muscle activities of the the superficial masseter on both sides.

3. Decrease the maximum force of the right superficial masseter with 50 %. What happens with the joint reaction forces? Can you explain the result? Have also a look at the estimated muscle activities. What happens here.

Joint forces in a mandible with unilateral hypoplasia before and after mandibular distraction osteogenesis

A simulation study using a patient-specific musculo-skeletal model

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The patient

- 12 year old boy
- Unilateral hypoplasia of the right ramus
- Due to juvenile idiopathic arthritis
- The right ramus was distracted with 15 mm using distraction osteogenesis

From: Cattaneo, University of Aarhus, PhD thesis

Inclination of articular eminence is more flat on the affected side

- 12 year old boy
- Unilateral hypoplasia of the right ramus
- Due to juvenile idiopathic arthritis
- The right ramus was distracted with 15 mm using distraction osteogenesis

From: Cattaneo, University of Aarhus, PhD thesis
Questions

• Can we predict joint and muscle forces in the human masticatory system before and after mandibular distraction osteogenesis?

• Are the inclination of the articular eminences optimised in order to minimize the loading on the temporomandibular joints?

Tool:
Musculo-skeletal modeling based on inverse dynamics using AnyBody

The AnyBody Modeling System

• Software for modelling and analysis of the musculo-skeletal system

• Main features:
  – Based on inverse dynamics and optimisation principles
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Patient specific mandible model

- Based on a CT scan of the patient
- Shortened right ramus
- 24 hill-type muscles
- On the affected side (Cattaneo et al., Comput Methods Biomech Biomed Engin, 2005; 8: 157-165):
  - masseter (17% weaker)
  - medial pterygoid (3% weaker)
  - lateral pterygoid (6% weaker)
- Inclination of articular eminence is more flat on the affected side

A generic model has been validated:

Input in the patient model

Before distraction
After distraction

Clenching force between the central incisors

191 N
191 N
Calculation scheme

Parameter study and optimization before distraction

Input: 191 N clenching force on the central incisors

Parameters:
1. Inclination of articular eminence affected side (right)
2. Inclination of articular eminence unaffected side (left)

Objective:
Minimization of the average TMJ loading
Results: **before** distraction

Inclination angle affected side (right):

25.6 degrees

Inclination angle unaffected side (left):

35.9 degrees

TMJ force affected side (right):

169 N

TMJ force unaffected side (left):

164 N

Parameter study and optimization **after** distraction

15 mm distraction of the right ramus

Input: 191 N clenching force on the central incisors

Parameters:

1. Inclination of articular eminence affected side (right)
2. Inclination of articular eminence unaffected side (left)

Objective:

Minimization of the average TMJ loading
Results: after distraction

Inclination angle affected side (right):
29.4 degrees

Inclination angle unaffected side (left):
31.7 degrees

TMJ force affected side (right):
144 N

TMJ force unaffected side (left):
132 N

Before distraction

Inclination angle affected side:
25.6 degrees

Inclination angle unaffected side:
35.9 degrees

TMJ force affected side:
169 N

TMJ force unaffected side:
164 N

After distraction

Inclination angle affected side:
29.4 degrees

Inclination angle unaffected side:
31.7 degrees

TMJ force affected side:
144 N

TMJ force unaffected side:
132 N

More equal

Decrease
Conclusion

• Adaptation of the articular eminence takes place in order to minimize TMJ loading
  – Experimental confirmation is needed, especially after distraction
• For the same loading condition the TMJ loading decreases after correcting the asymmetry
• Pre-clinically testing of the mechanical consequences of a planned distraction

Online resources

• Department of Orthodontics, University of Aarhus
  www.odont.au.dk/or/
• The AnyBody Modeling System
  www.anybodytech.com
• The AnyBody Research Project
  www.anybody.aau.dk
• mdz@hst.aau.dk

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