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

Mark de Zee

ANYBODY RESEARCH PROJECT

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.

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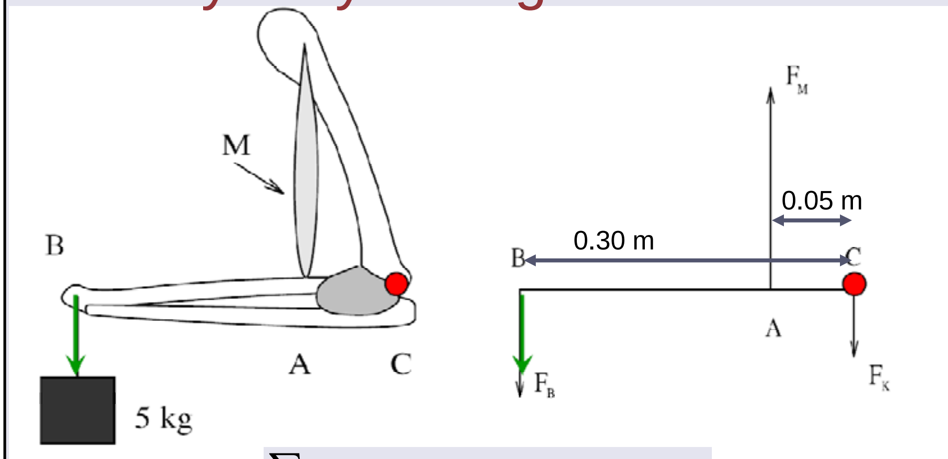
AnyBody: The general idea



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

$$F_m = \frac{14.72}{0.05} = 294 \quad N$$

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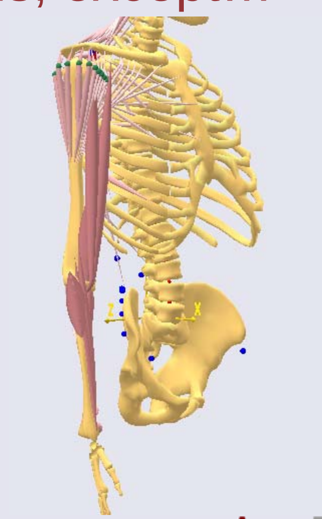
The same principle applies to more complex systems, except…



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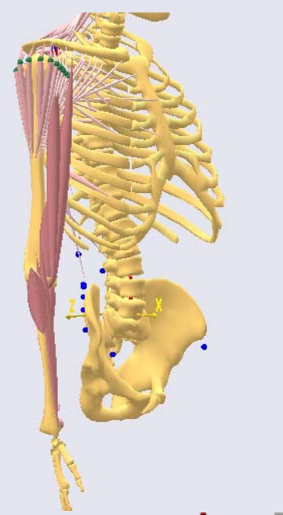
...we have too ”many” muscles!

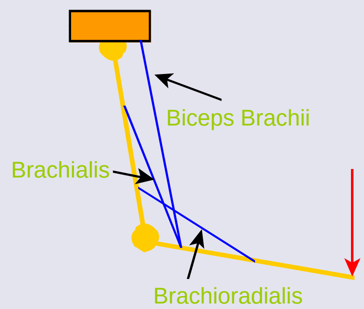
The same principle applies to more complex systems

- 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.



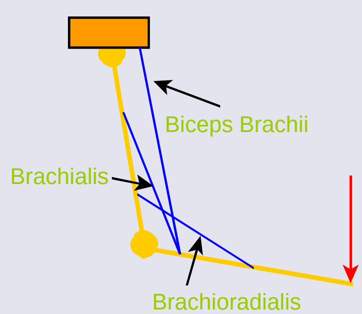
Calculation of muscle force

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

$$G(\mathbf{f}^{(\mathbf{M})})$$

Subject to

$$\mathbf{Cf} = \mathbf{d}$$

$$f_i^{(M)} \geq 0, \qquad i \in \{1,..,n^{(M)}\}$$

Objective function. Different choices give different muscle recruitment patterns.

Equilibrium equations

Muscles cannot pull

Minimum fatigue formulation

Minimize maximum relative muscle load or minimize fatigue or maximize endurance

Minimize

$$\max\left(\frac{f_i^{(M)}}{N_i}\right), \qquad i \in \{1,..,n^{(M)}\}$$

"Max muscle activity"

Muscle force

Muscle strength.

Subject to

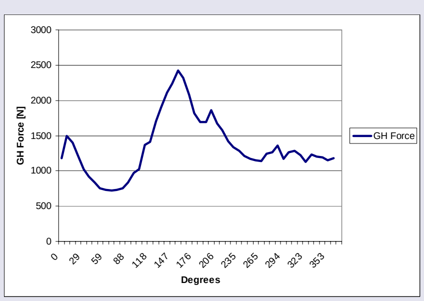
$$\mathbf{Cf} = \mathbf{d}$$

$$f_i^{(M)} \geq 0, \qquad i \in \{1,..,n^{(M)}\}$$

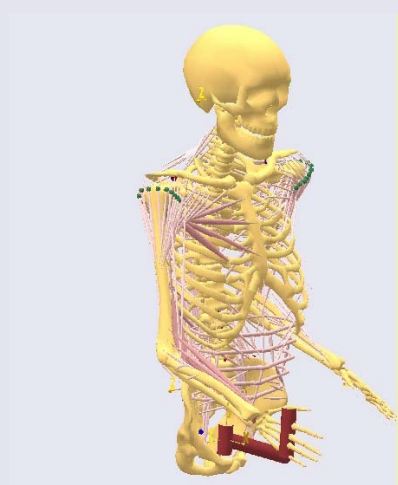
Message

- 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

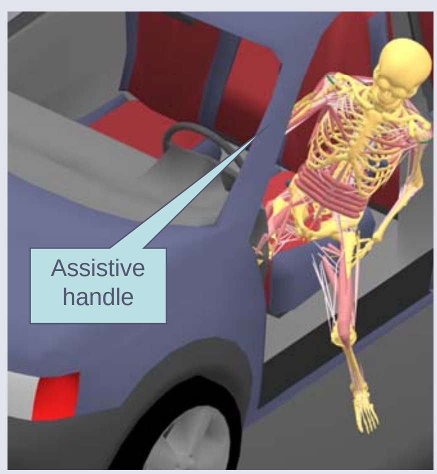


1. Wheelchair propulsion

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

2. Egress

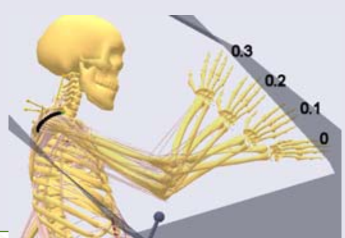
- Ageing population.
- Limited muscle strength.
- Arthritis in the knees.
- Investigation of handle position.

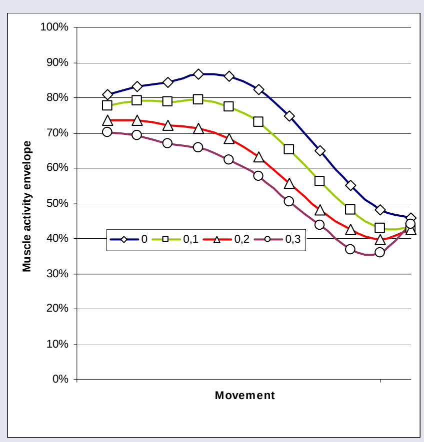


The Movement

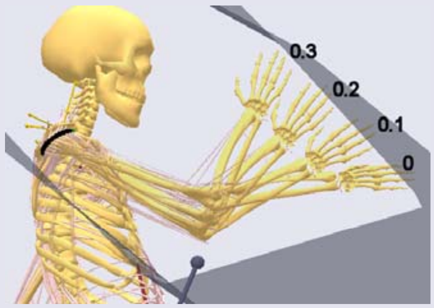
Muscle effort

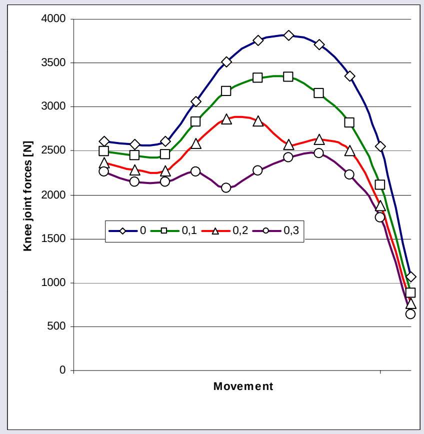
- High handle position preferable
- Near-standing positions less strenuous





Knee joint forces





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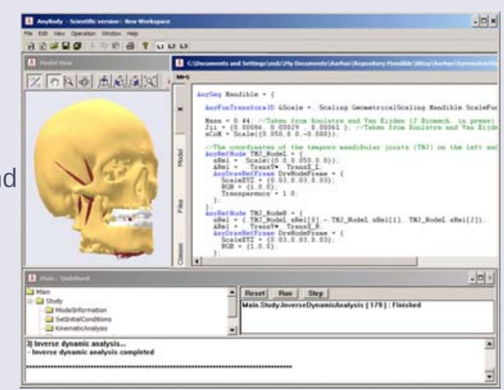
The AnyBody Modeling System

- 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



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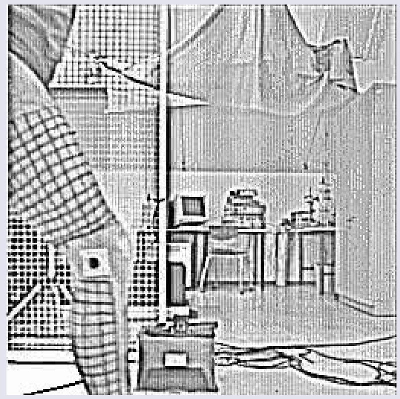
Assumptions and limitations

- With AnyBody one can only model skilled movements
- Explosive movements cannot be modelled due to wobbling masses



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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.

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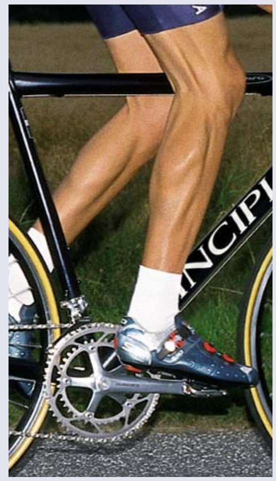
Muscles – types

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



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Muscles – contraction types

- *Concentric* contraction
  - Muscle shortens
- *Isometric* contraction
  - Muscle keeps the same length
- *Eccentric* contraction
  - Muscle lengthens

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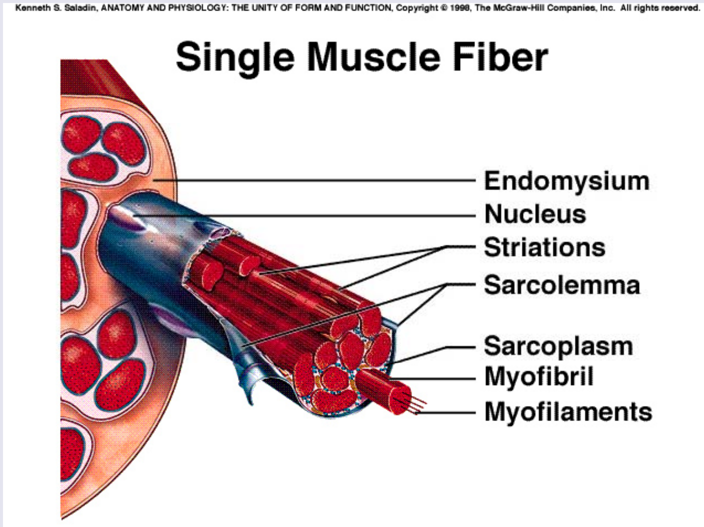
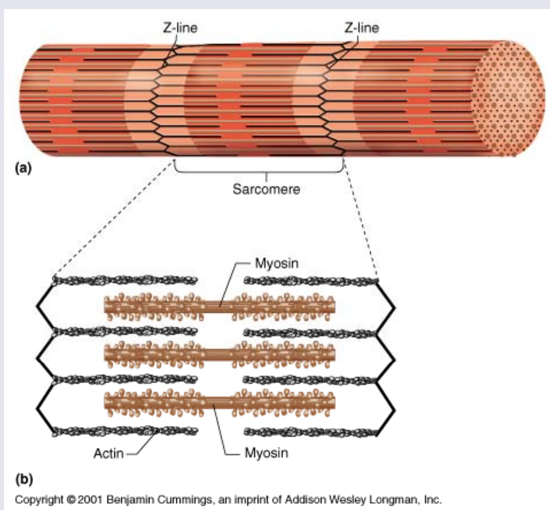
Single muscle fiber



Cross-bridge theory (Huxley)



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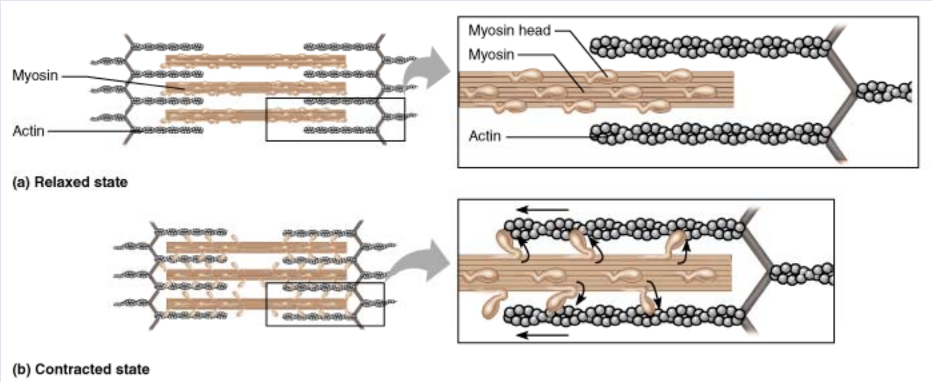

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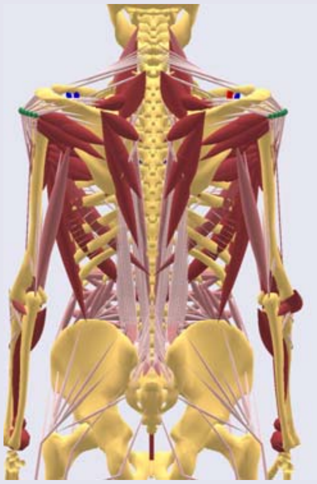
Modeling muscle geometry in AnyBody

Reality

Model



What are the differences?

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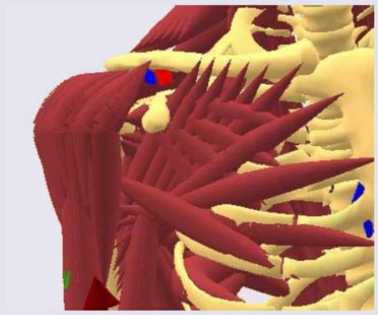
Elements of a modeled muscle

- Kinematics: The origin-insertion path
- Strength
  - Dependent on physiological properties
  - Depending on operating state



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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

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Minimum fatigue formulation

Minimize maximum relative muscle load or minimize fatigue or maximize endurance

Minimize

$$\max\left(\frac{f_i^{(M)}}{N_i}\right), \qquad i \in \{1,..,n^{(M)}\}$$

"Max muscle activity"

Muscle force

Muscle strength.

Subject to

$$\mathbf{Cf} = \mathbf{d}$$

$$f_i^{(M)} \geq 0, \qquad i \in \{1,..,n^{(M)}\}$$

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Muscle strength depends on:

- The amount of fibres parallel with each other i.e. Cross-sectional area
- The neural drive
- Length
- Shortening /lengthening velocity

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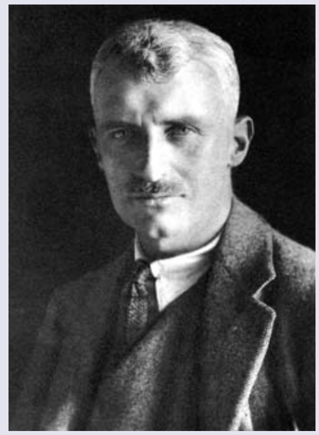
A.V. Hill (1886-1977)

- Nobel prize in 1922
- Muscle mechanics
- Muscle energetics



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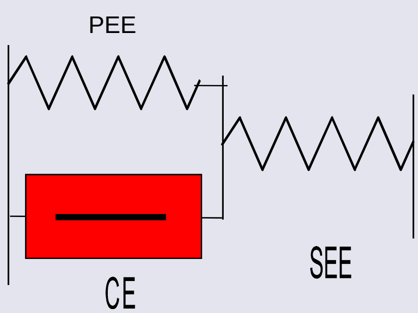
Hill Muscle Model (1)



- CE = Contractile Element
- SEE = Series Elastic Element
- PEE = Parallel Elastic Element

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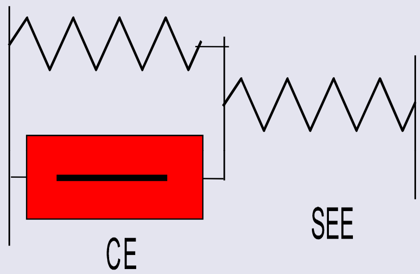
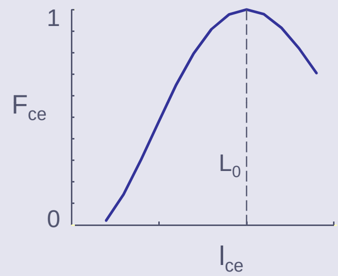
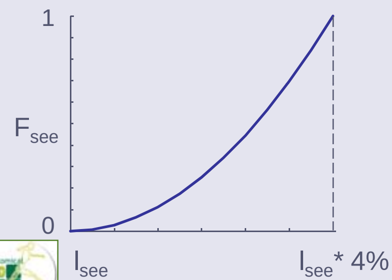
Hill Muscle Model (2)







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Demo mandible model (Monkey see – Monkey do

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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.

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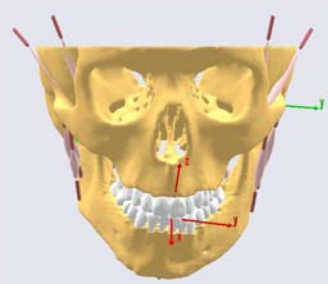
Joint forces in a mandible with unilateral hypoplasia before and after mandibular distraction osteogenesis

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



Mark de Zee, P.M. Cattaneo, M. Dalstra, J. Rasmussen, P. Svensson, B. Melsen

Dept. of Orthodontics, University of Aarhus, Denmark

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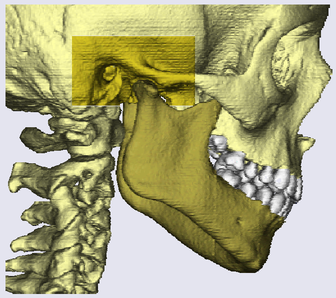
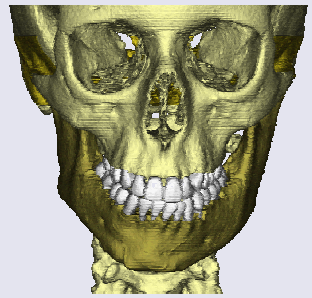
The patient





- 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

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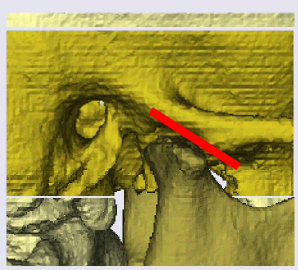
The patient



Inclination of articular eminence is more flat on the affected side

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- 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

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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

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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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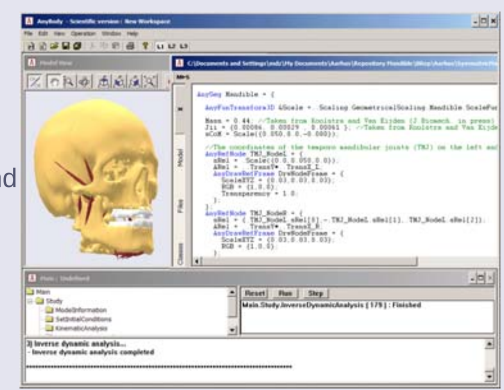

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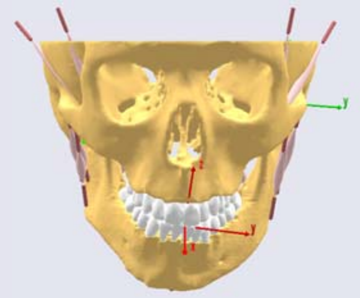
Patient specific mandible model

- 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:

de Zee et al., *J. Biomech*, 40 (2007) 1192–1201.

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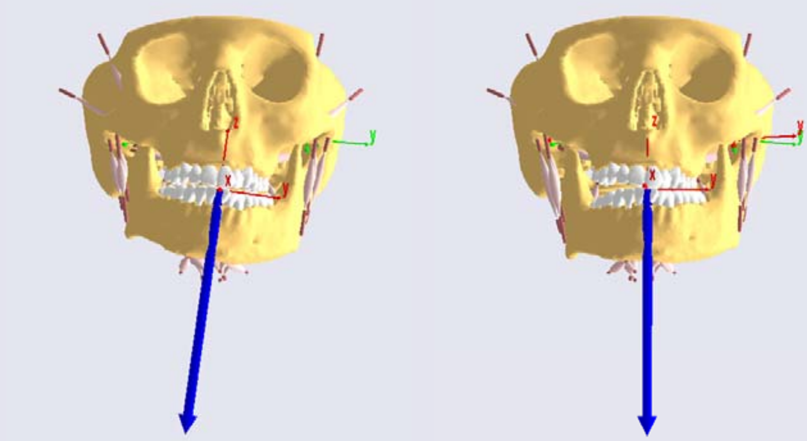
Input in the patient model

Before distraction

After distraction



Clenching force between the central incisors

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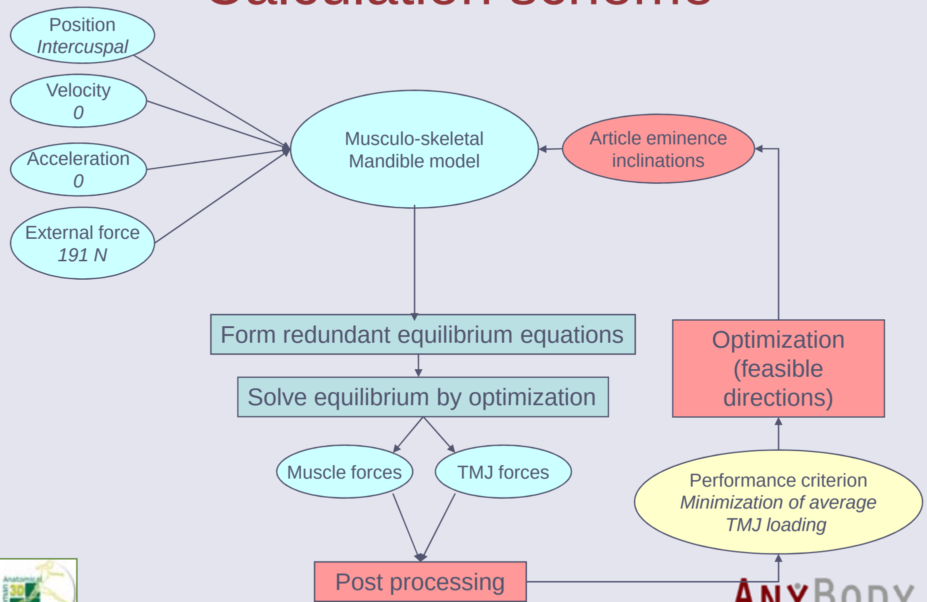
Calculation scheme



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Parameter study and optimization **before** distraction

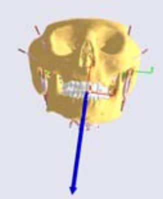
Input: 191 N clenching force on the central incisors

Parameters:

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

Objective:

Minimization of the average TMJ loading



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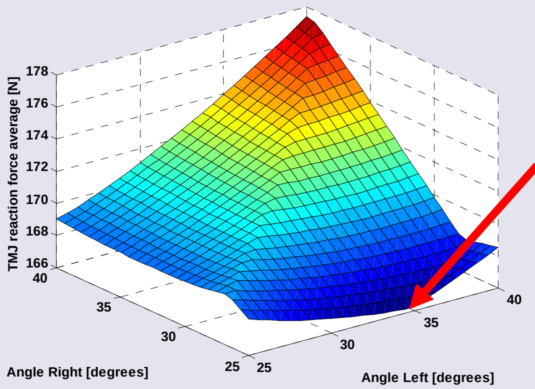
Results: **before** distraction



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

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Parameter study and optimization **after** distraction

15 mm distraction of the right ramus

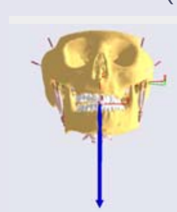
Input: 191 N clenching force on the central incisors

Parameters:

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

Objective:

Minimization of the average TMJ loading



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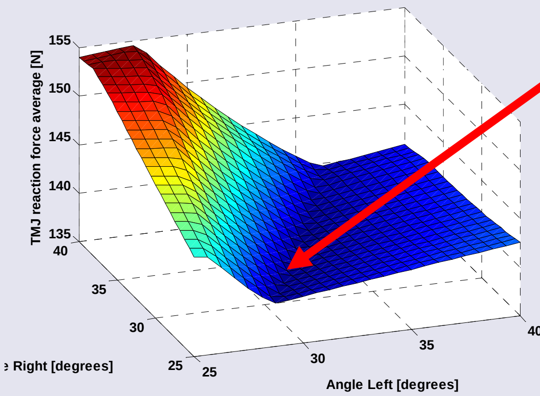
Results: **after distraction**



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

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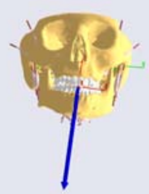
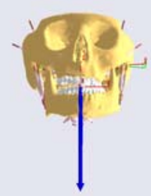
Before distraction		After distraction
		
Inclination angle affected side:		Inclination angle affected side:
25.6 degrees	More equal →	**29.4 degrees**
Inclination angle unaffected side:		Inclination angle unaffected side:
35.9 degrees		**31.7 degrees**
TMJ force affected side:		TMJ force affected side:
169 N	Decrease →	**144 N**
TMJ force unaffected side:		TMJ force unaffected side:
164 N		**132 N**

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

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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

Acknowledgements

Villum Kann Rasmussen foundation

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