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AIF - Zebris cooperation project

A variable finite element model of the human masticatory system for different loading conditions

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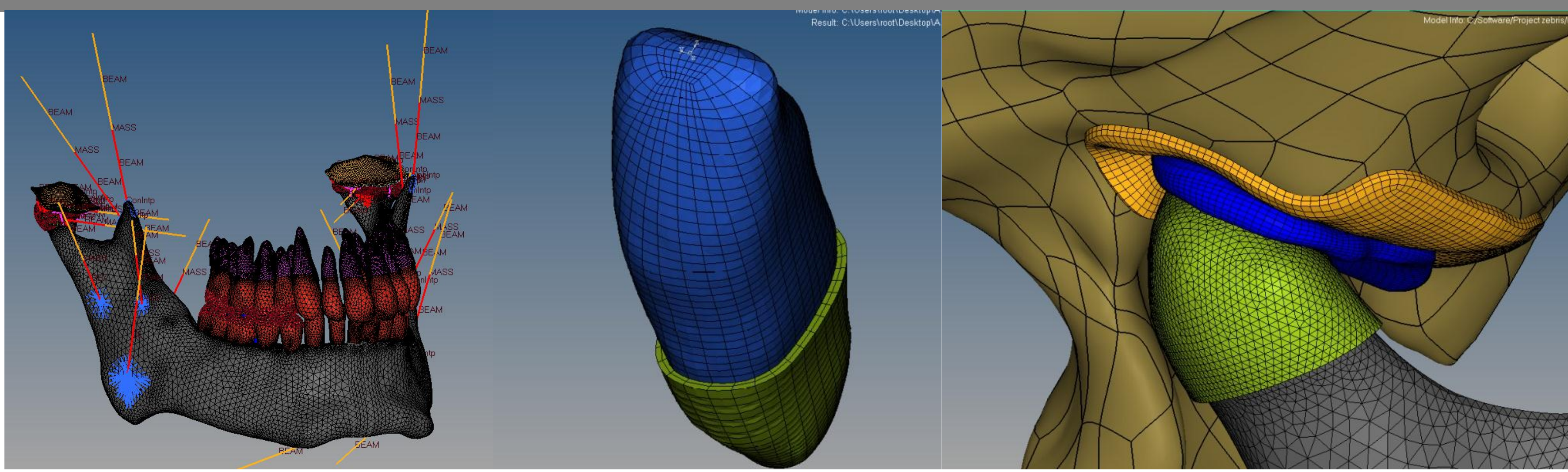

Outline

1. Motivation: AIF - Zebris cooperation project - goal and scope
2. The different components of the masticatory system:
   - Brief description
   - Modelling: Overview over state of the art
3. Generation of the finite element model: Workflow and major challenges
4. Visualization of results for various loading situations
5. Summary

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Motivation

AIF - Zebris cooperation project

Development of a system to capture the biting/chewing function of the jaw under occlusal forces to optimize dentures manufactured with CAD/CAM and to improve dental implant planning

Partners

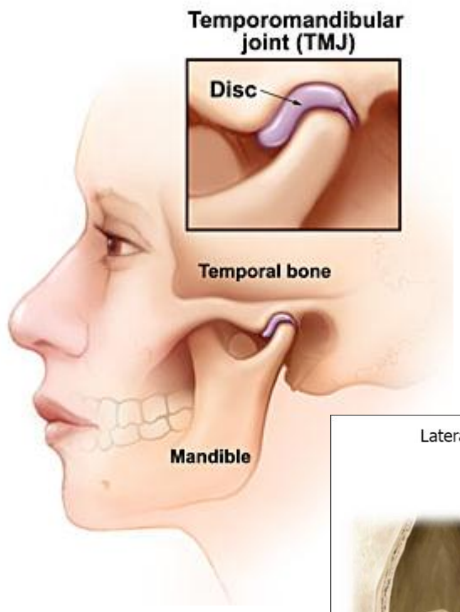
- Zebris medical GmbH
- Ernst Moritz Arndt Universität Greifswald
- Karlsruhe Institut für Technologie (KIT)
- Ingenieurbüro Steinman & Reinke

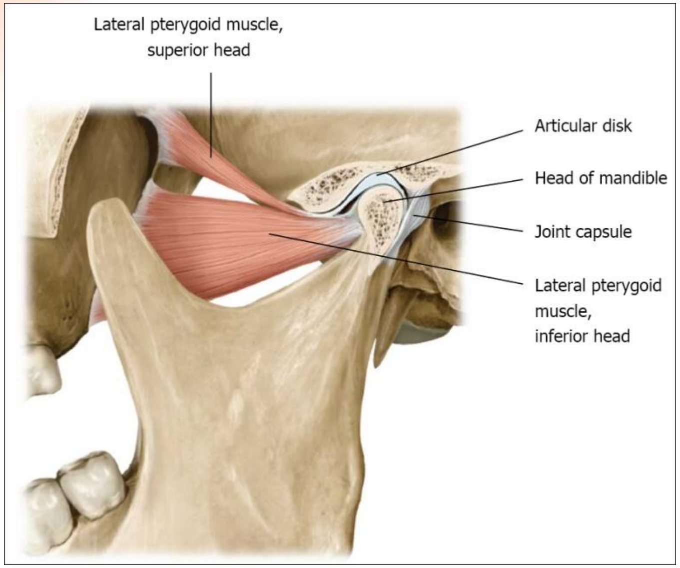
Goal →

Creation of a variable finite element model to determine the deformation of the jaw and the displacement of the teeth under functional loads

The masticatory system - TMJ

Temporomandibular joint (TMJ)





- Composed of:
  - Mandibular condyles
  - Articular surface of the temporal bone
  - Capsule
  - Articular disc
  - Ligaments
  - Lateral pterygoid muscle
- Configuration varies from person to person
- Lateral pterygoid muscle: Upper head always inserts on the condyle, in 60% of specimens it also inserts on the disc-capsule complex

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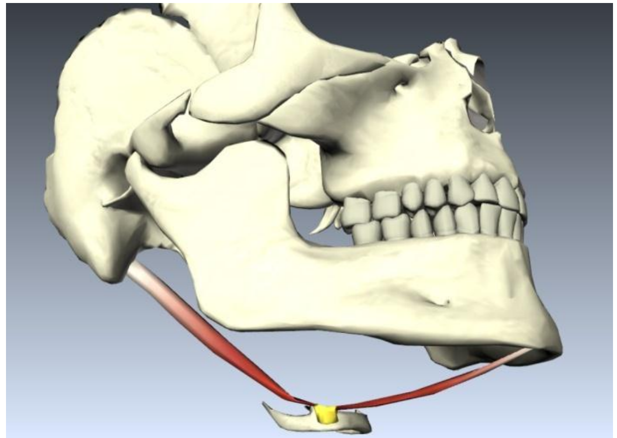
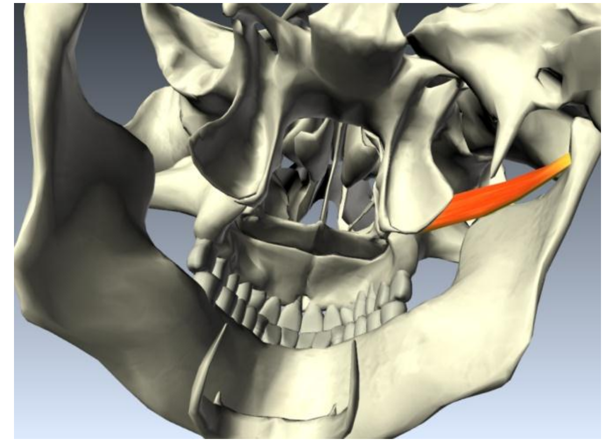
The masticatory system - Muscles

www.biodigitalhuman.com

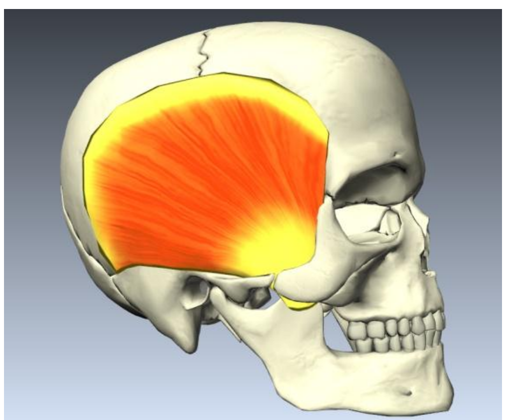
Principal muscles responsible for opening (upper row) and closing (lower row) the jaw



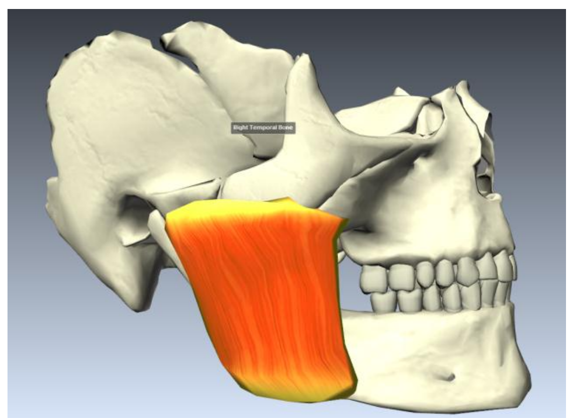
Digastricus



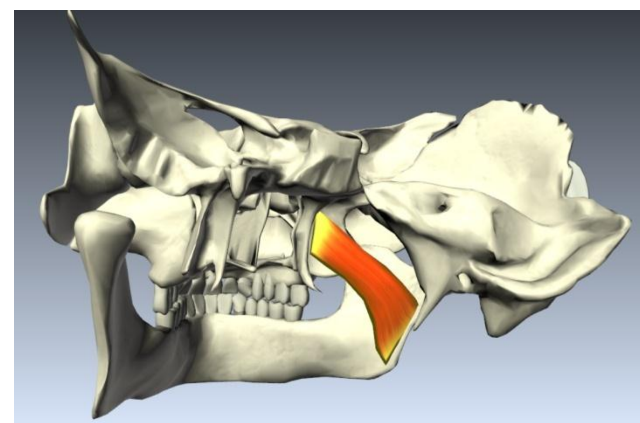
Lateral pterygoid



Temporalis

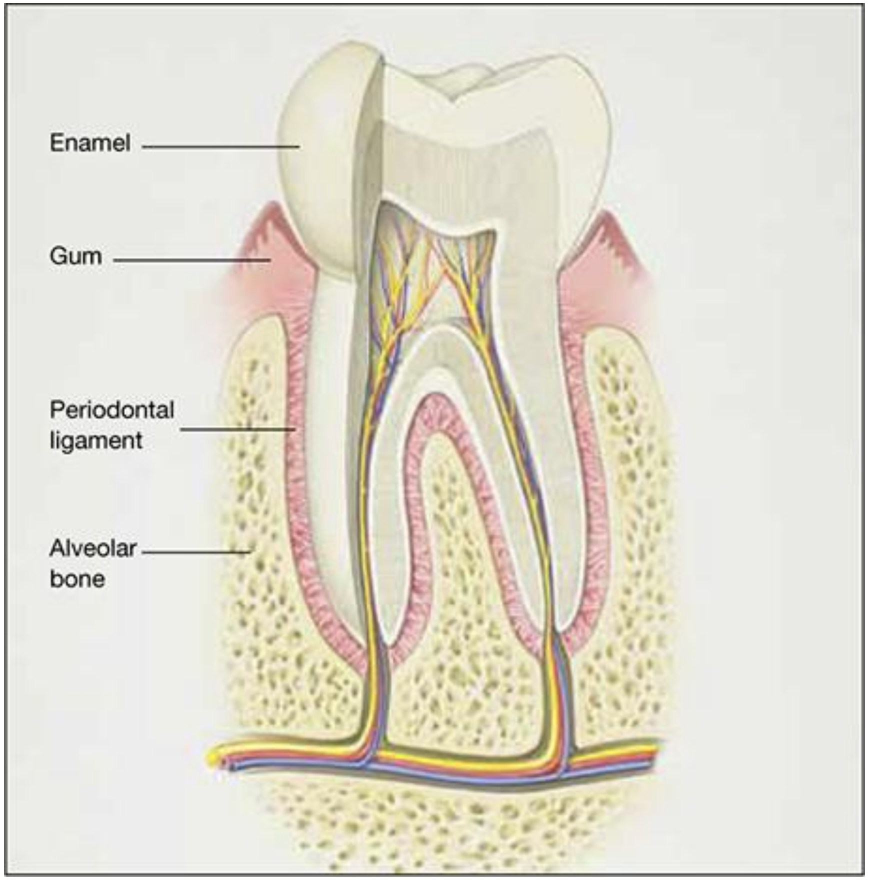


Masseter



Medial pterygoid

The masticatory system - PDL
Periodontal ligament (PDL)



- Connective tissue that attaches the teeth to the alveolar bone.
- Responsible for tooth mobility
- Average thickness of 0.25 mm.

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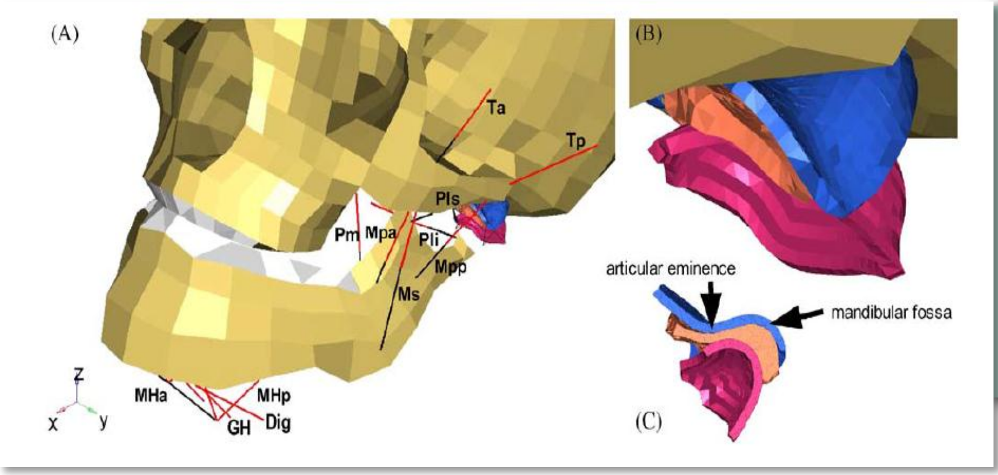
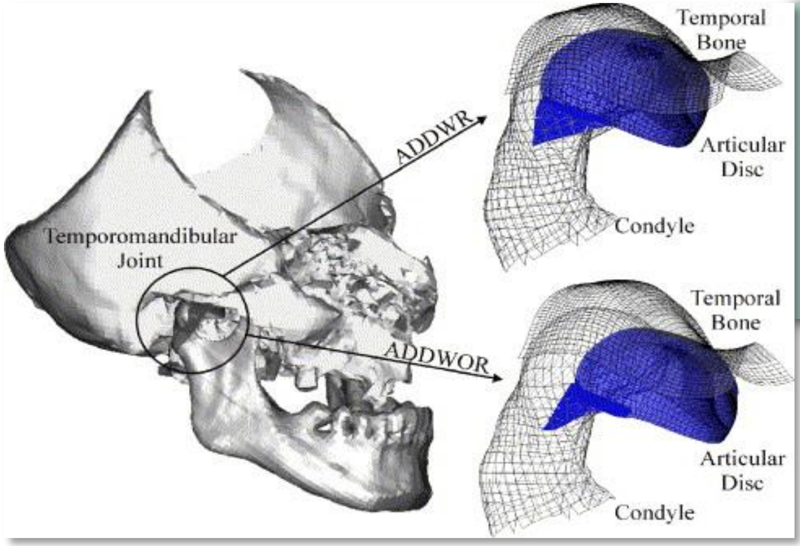
State of the art - TMJ



J.H Koolstra,
T.M.G.J van Eijden (2005)

- Articular disc modeled with an hyperelastic model



Perez de Palomar et al. (2006)

- Articular disc modeled with a poroelastic (anisotropic) material model.

**Images taken from corresponding papers*

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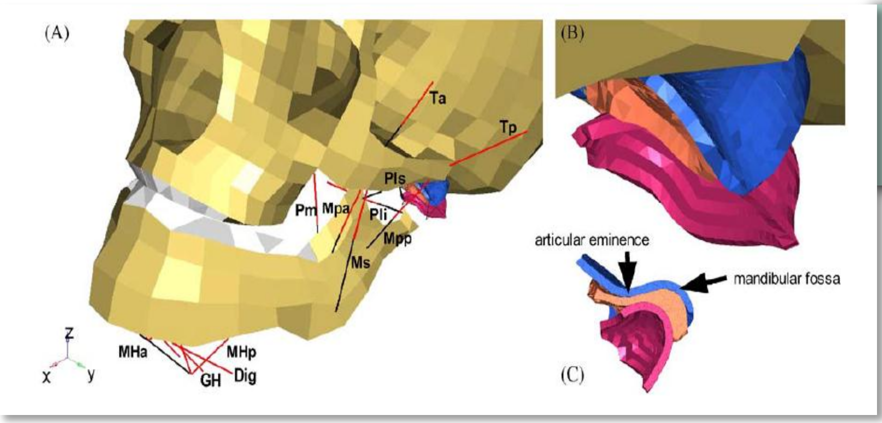
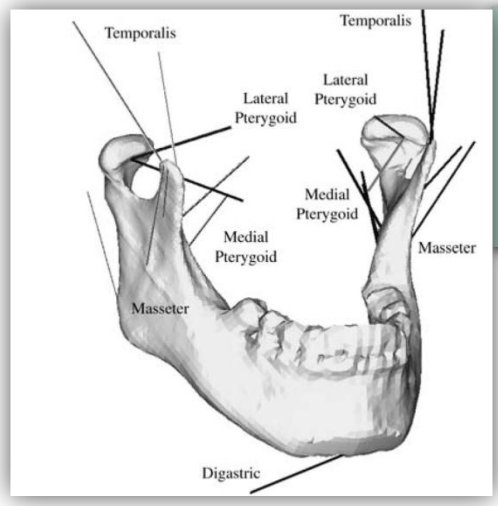
State of the art - Muscles



J.H Koolstra,

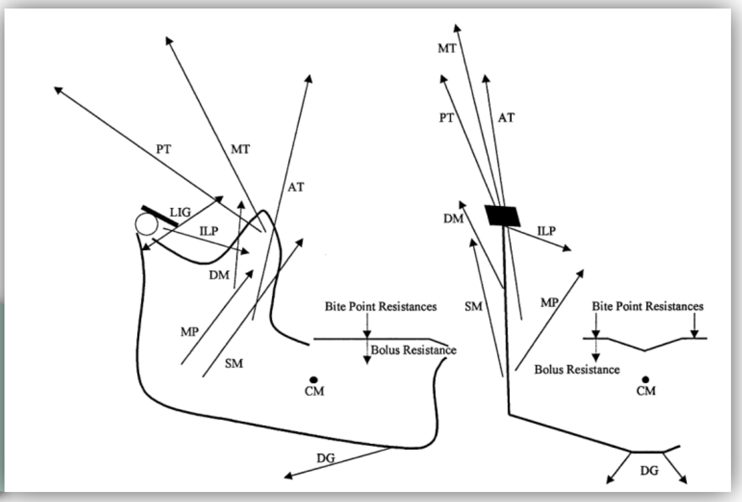
T.M.G.J van Eijden (2005)

Muscles fibers are modeled with the Hill muscle model, tendon tissue is either incorporated or modeled separately.

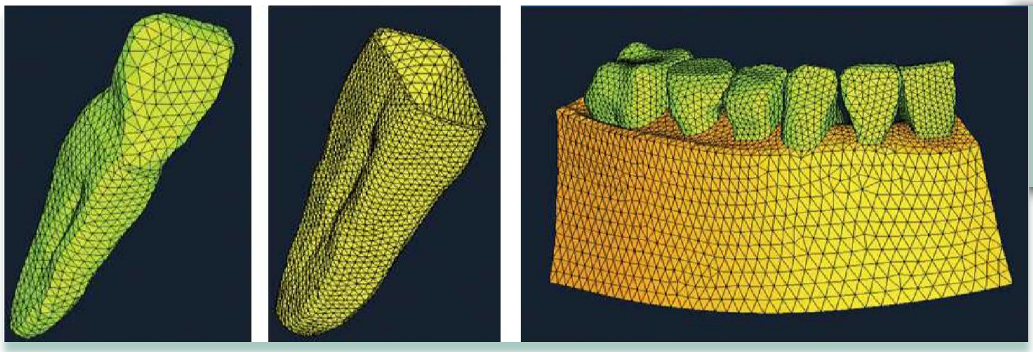


Perez de Palomar et al. (2007)

G.E.J Langenbach, A.G Hannam (1999)



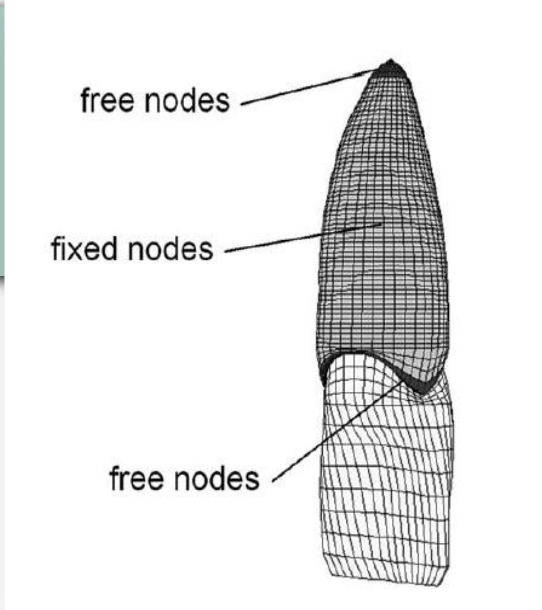
State of the art – PDL (Periodontal ligament)

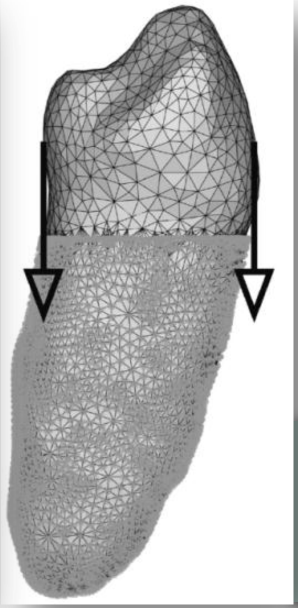


Weijun Yan et al. (2012)

- Discrepancies in stiffness in the literature up to six orders of magnitude
- Modeled with elastic, hyperelastic and viscoelastic material models

Arturo N. Natali et al. (2004)





Hohmann et al. (2011)

Creation of the finite element model

Creation of the geometry

- Segmentation
- Geometry treatment
- Creation of soft tissue

Model discretization

- Element type
- Mesh resolution
- Static or dynamic?

Material model assignment

- Bones
- PDL
- Cartilage
- Discus articularis

- Geometry accuracy is limited by resolution of CT scans
- Soft tissues are not visible in CT scans
- No MRI scans available

- A good FE mesh is required
- Appropriate element types are needed
- Computational time must be reasonable (statics vs. dynamics)

- No agreement in the literature for many of the material properties
- Some material parameters provided in the literature lead to unstable results

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Creation of the finite element model

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Boundary conditions

- Muscle forces
- Constraints
- Temporomandibular joint

Results evaluation

- Visualization
- Validation

- Stabilization of analysis by considering dynamics
- Computationally impractical to model the process in its natural time period

- Experimental data are limited
- Strong variance of parameters between different subjects

Segmentation

Software: Mimics 14 (Materialise, Belgium, 2010)

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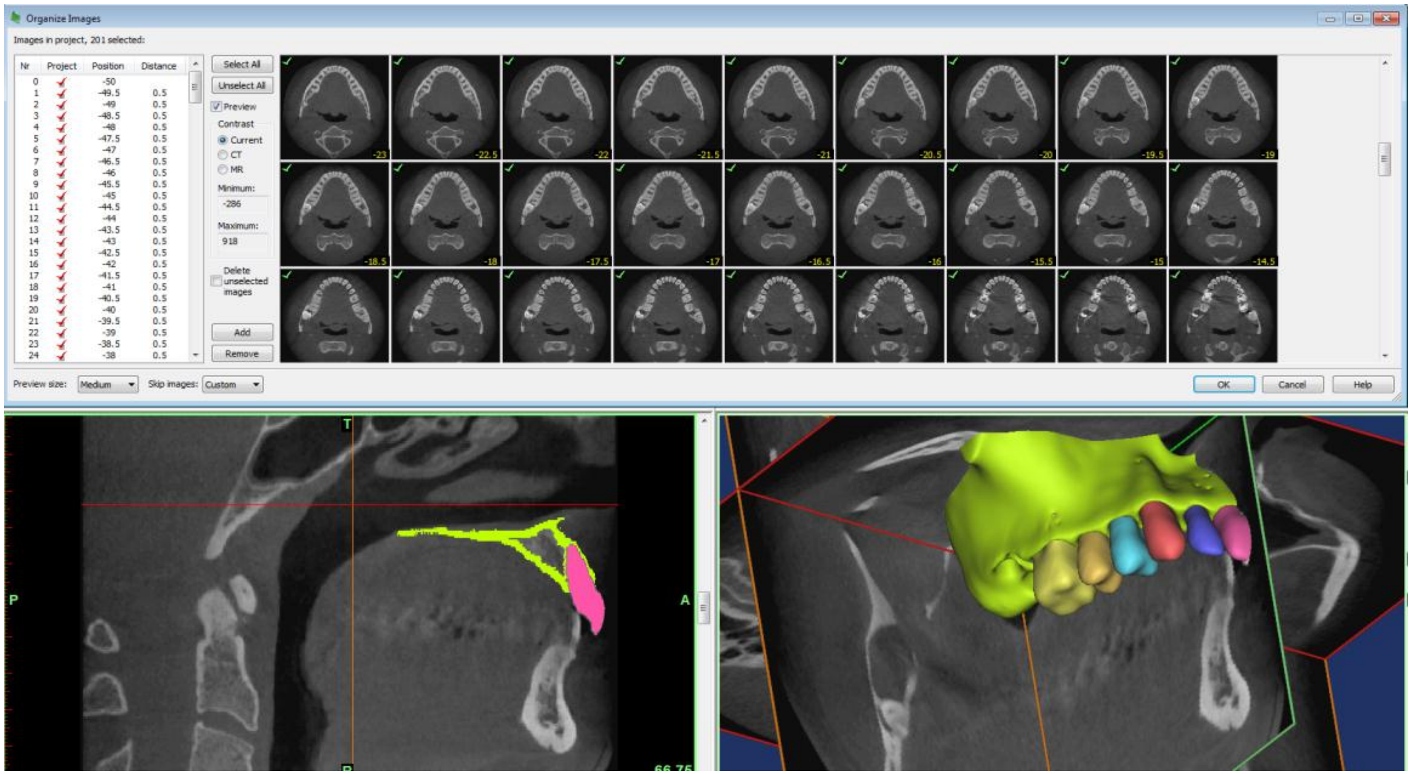
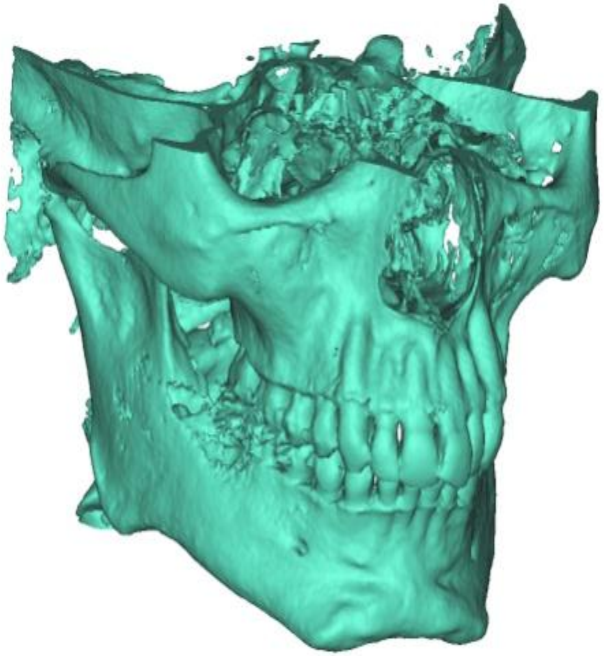


Geometry is obtained by outlining the contour of the desired object in each slide.

Segmentation

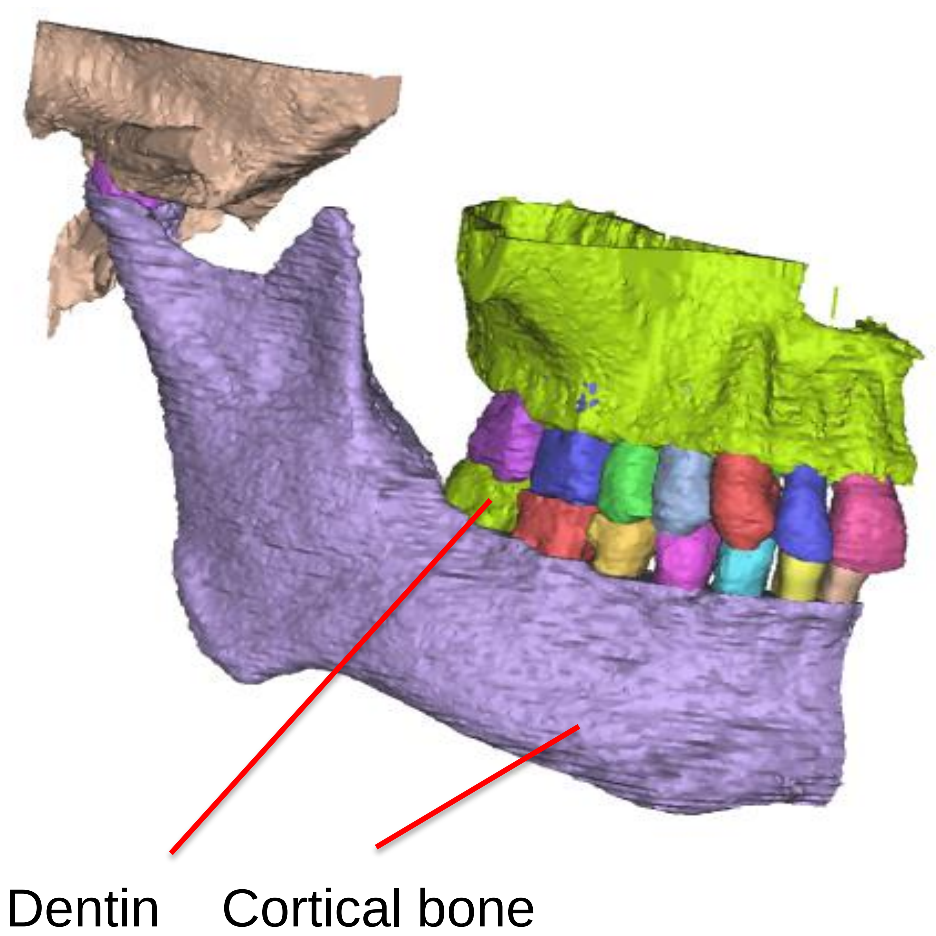
Software: Mimics 14 (Materialise, Belgium, 2010)



Grayscale value of the different components is very similar → Automatic segmentation results in a single part

Segmentation

Software: Mimics 14 (Materialise, Belgium, 2010)



Requirement

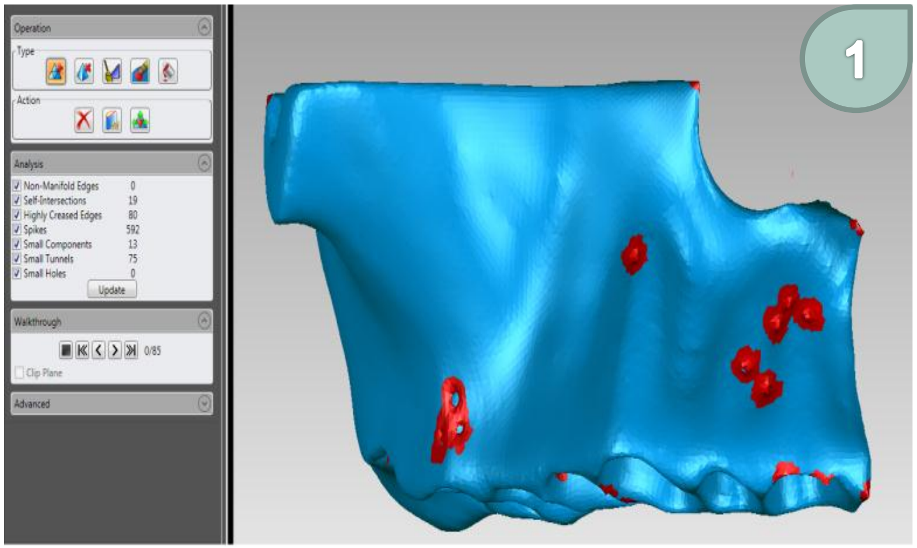
Geometries of the components must be separated for material assignment and for motion control

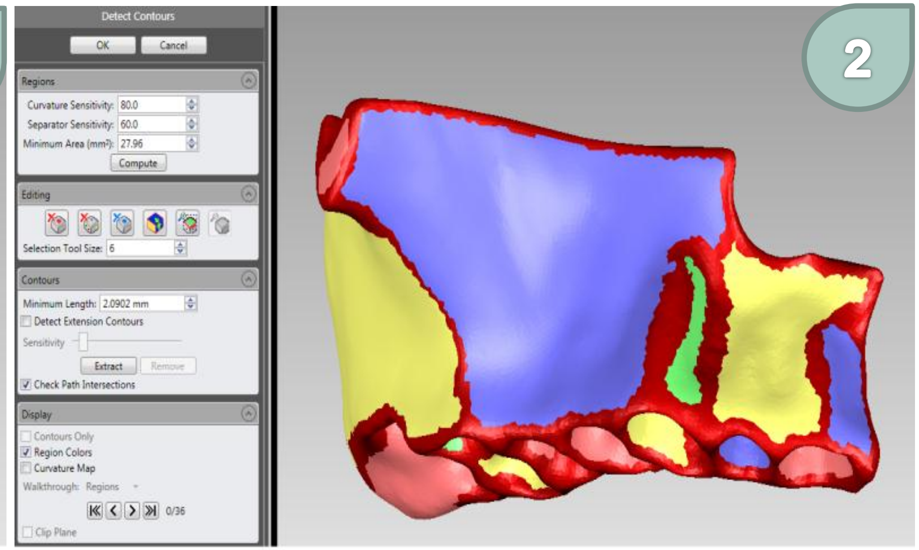
Geometry must be manually segmented

Geometry treatment

Software: Geomagic Studio12 (Geomagic Inc, USA, 2010)

Steps to create a geometry useful for FE modeling



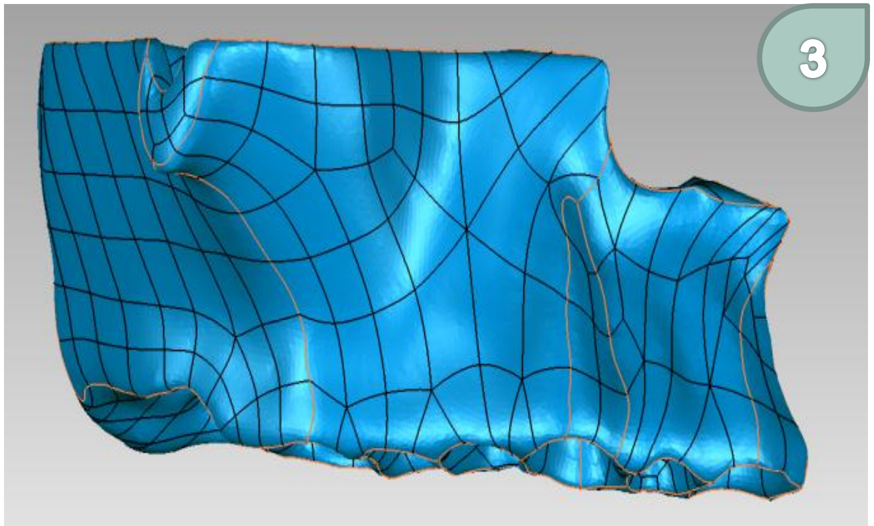


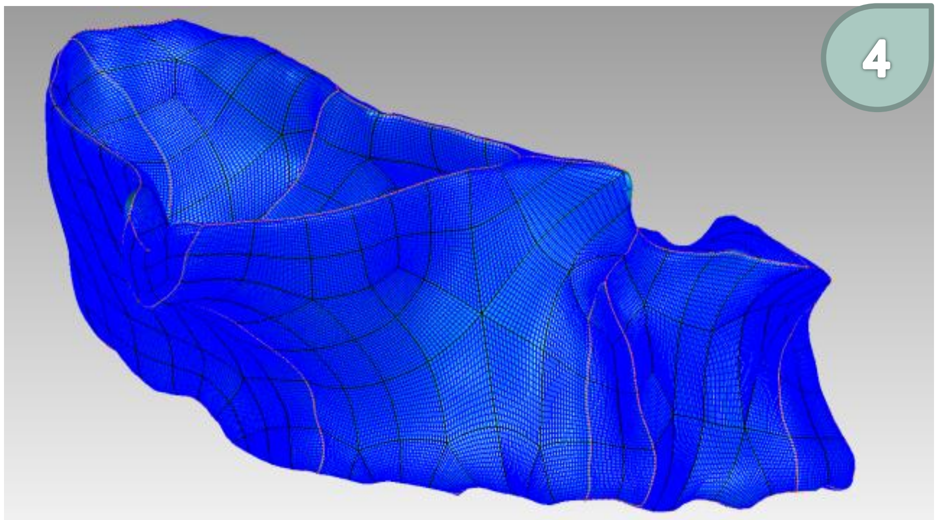
1. Repairing artificial holes and spikes
2. Creating contour lines to define major surfaces

Geometry treatment

Software: Geomagic Studio12 (Geomagic Inc, USA, 2010)

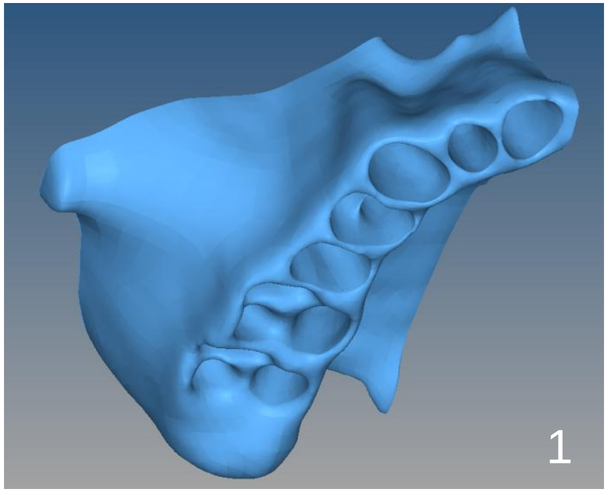
Steps to create a geometry useful for FE modeling

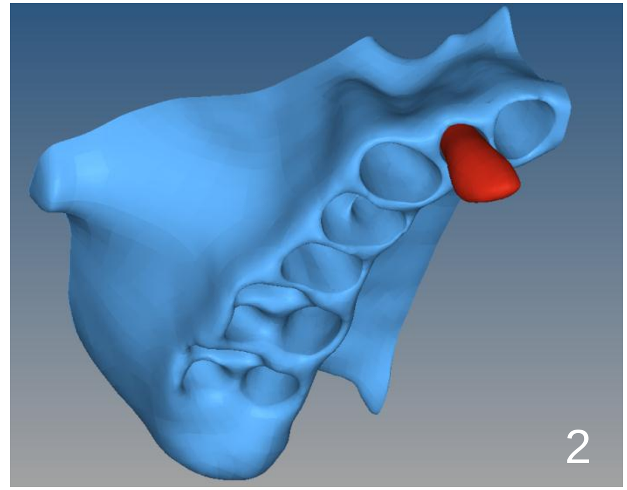


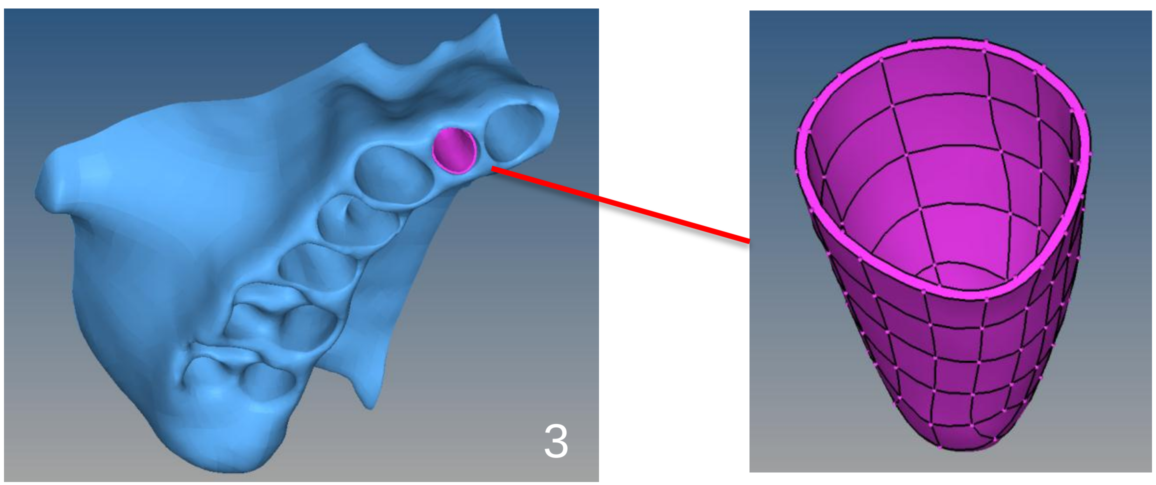


3. Placing patches over the major areas
4. Defining NURBS over the patches

Creation of soft tissue – Periodontal ligament







1. Alveoles are created with expanded teeth
2. Normal sized teeth are placed
3. Void space defined as PDL

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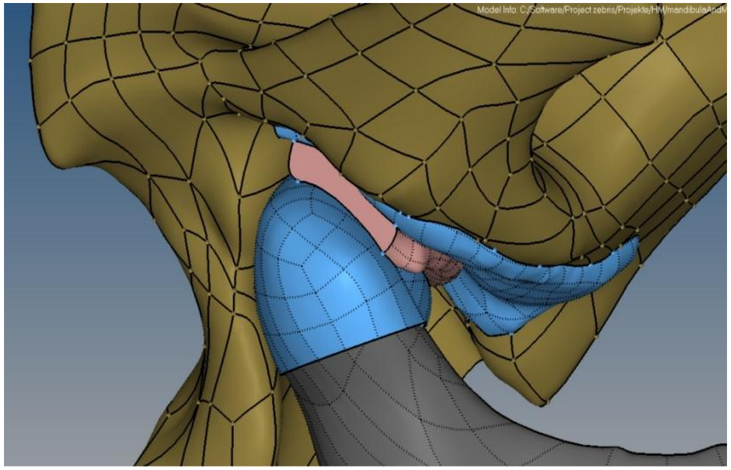
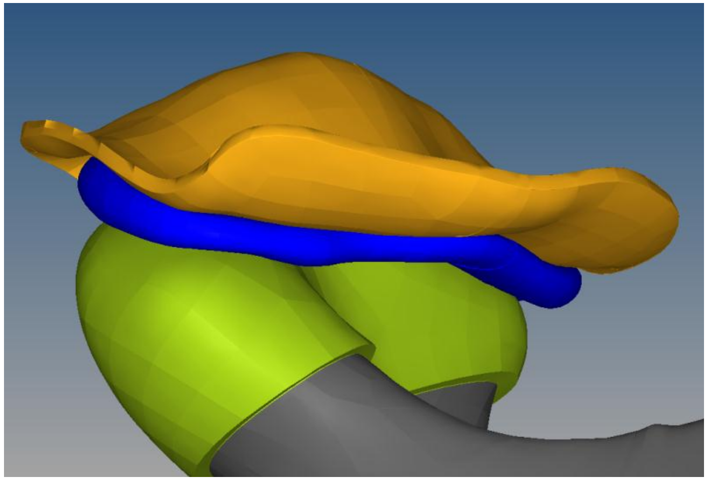
Creation of soft tissue – Temporomandibular joint



Previous geometries of the disc were not adequate



Current geometry of the TMJ

The articular disc and cartilage model were obtained through an iterative (manual) process

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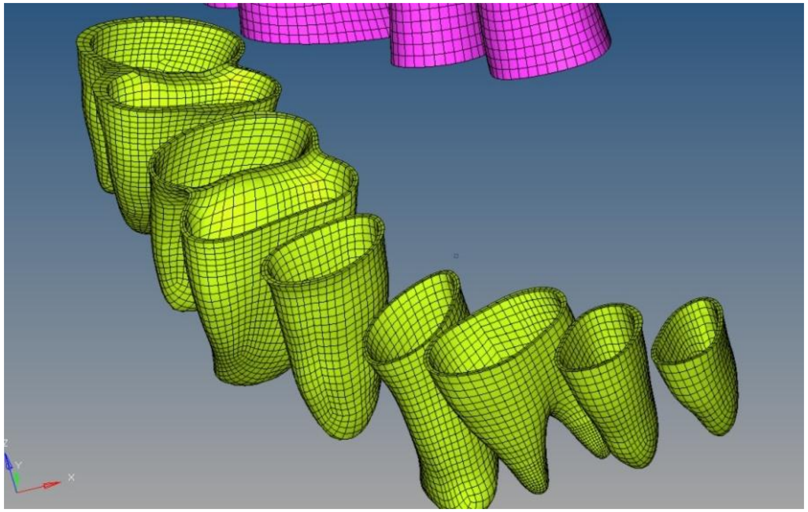
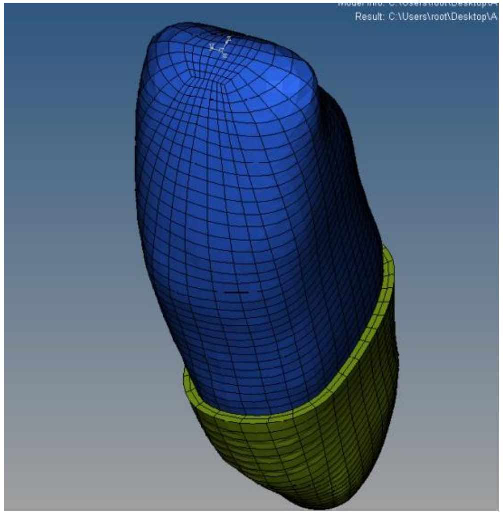
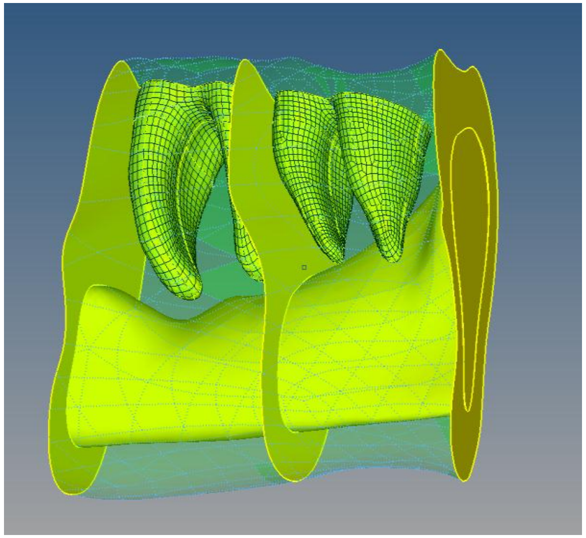
Model discretization

Software: Hypermesh 11 (Altair, USA, 2012)







- Geometry presents major challenges for a hexahedral mesh

Therefore

- Model is currently meshed mostly with tetrahedral elements

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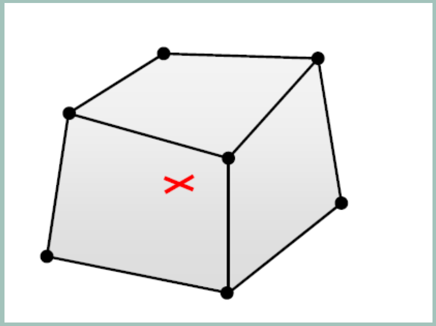
Finite element software

- Initial simulations of individual components were performed in ANSYS 14 as non linear static problems using a implicit method.
- Convergence was a major problem in the complete model.
- Explicit time integration is more efficient for highly nonlinear static problems, especially for three-dimensional problems involving contact and large deformations.
- LS-DYNA explicit solver showed a great reduction in computational time (total number of elements > 1.8 million for the full model) and avoids convergence problems altogether. *Artifacts arising from a dynamic approach must be avoided .*

Model discretization

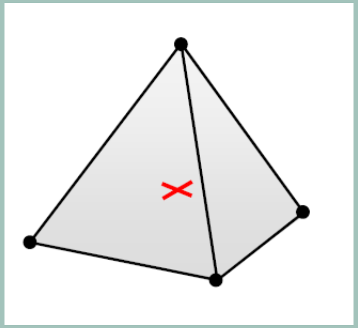
Software: LS-DYNA R6.1 (LSTC, USA, 2013)



Hexahedral element

ELFORM = 1

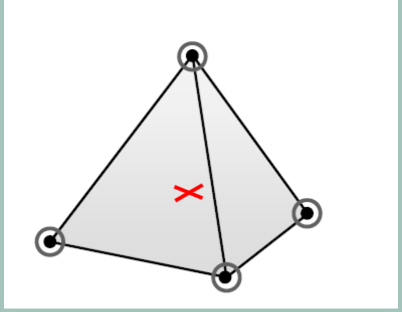
- Underintegrated constant stress
- Efficient and accurate
- Needs hourglass stabilization



Tetrahedral element

ELFORM = 10

- 1 point constant stress
- Volumetric locking – stiff behaviour

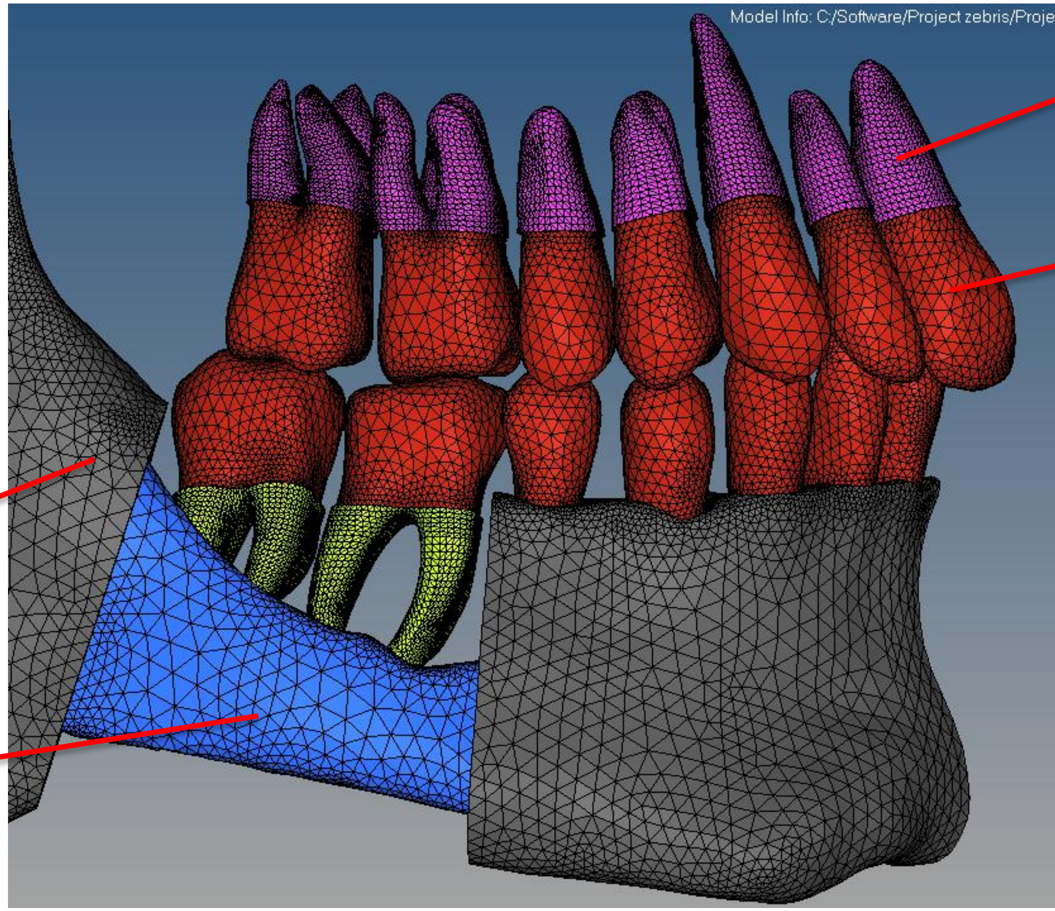


Tetrahedral element

ELFORM = 13

- 1 point constant stress with nodal pressure averaging
- Alleviated volumetric locking

Model discretization



PDL

Tooth

Cortical Bone

Spongy Bone

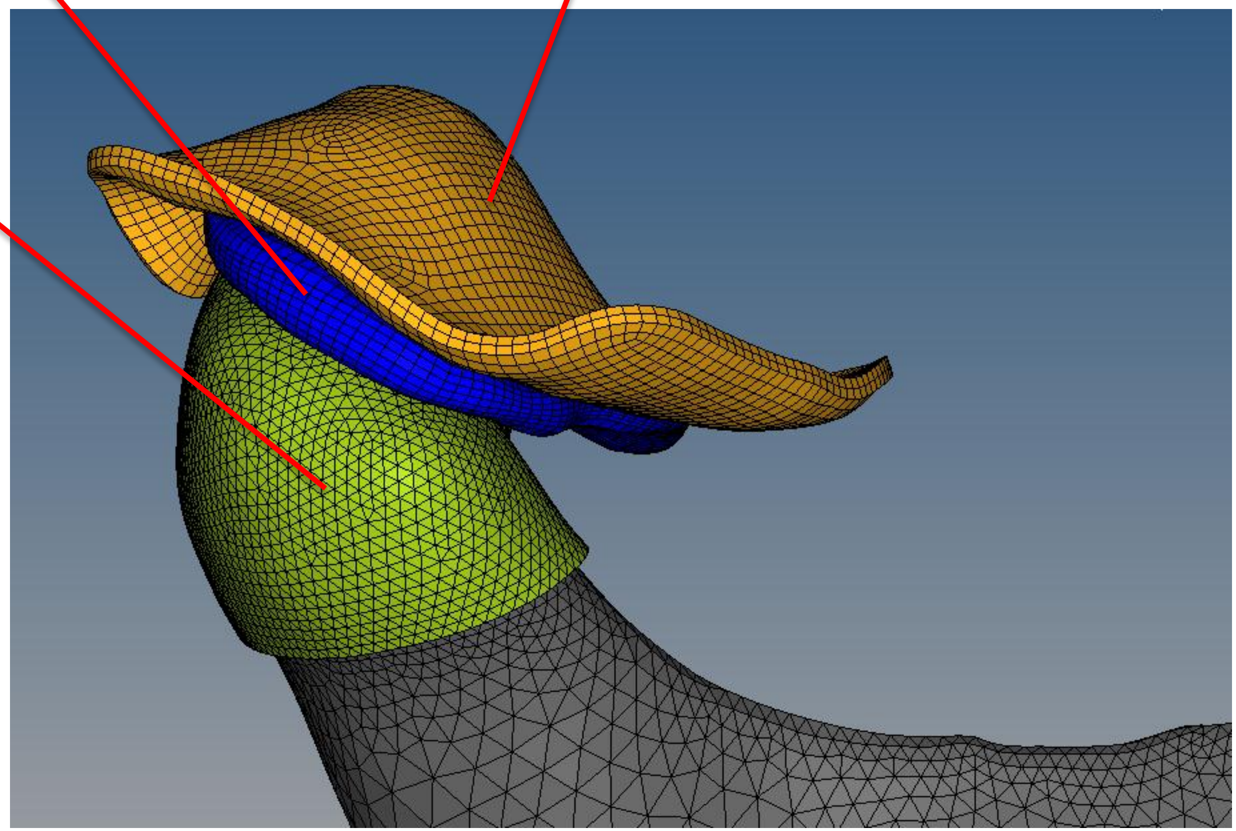
Components discretized with tetrahedral elements with alleviated locking

Model discretization

Articular disc : hexahedra

Fossa cartilage : hexahedra

Condyle
cartilage:
Tetrahedra



Total number of elements > 900.000
(symmetric model)

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Material assignment

Material	Constitutive law	Source of material parameters
Corticalis	Linear elastic	CES Edupack 2012
Spongiosa	Linear elastic	CES Edupack 2012
Dentin	Linear elastic	CES Edupack 2012
Articular disc	Viscoelastic (Mooney Rivlin)	Koolstra et. al
Cartilage	Hyperelastic (Mooney Rivlin)	Koolstra et. al
PDL	Hyperelastic (1^{st} order Ogden)	*
Silicon (test bolus)	Viscoelastic	-

* Large discrepancies in the literature

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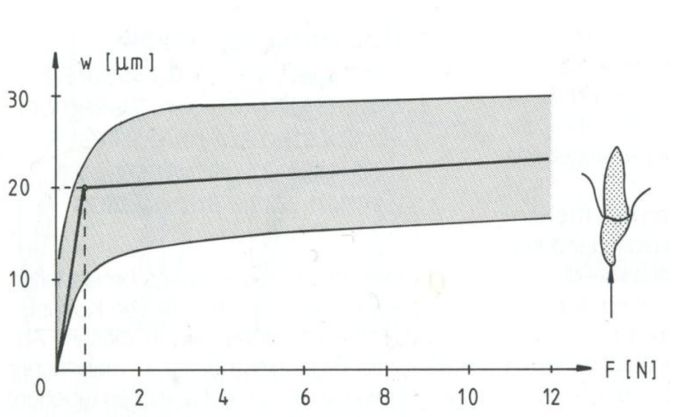
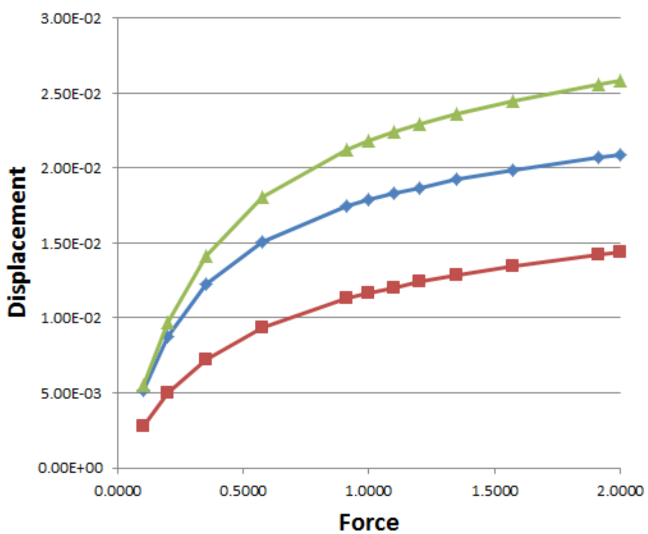
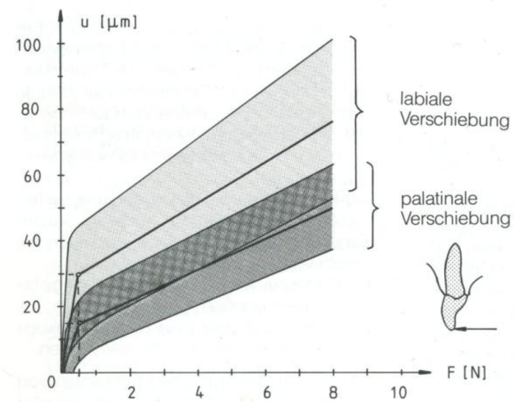
PDL hyperelastic model

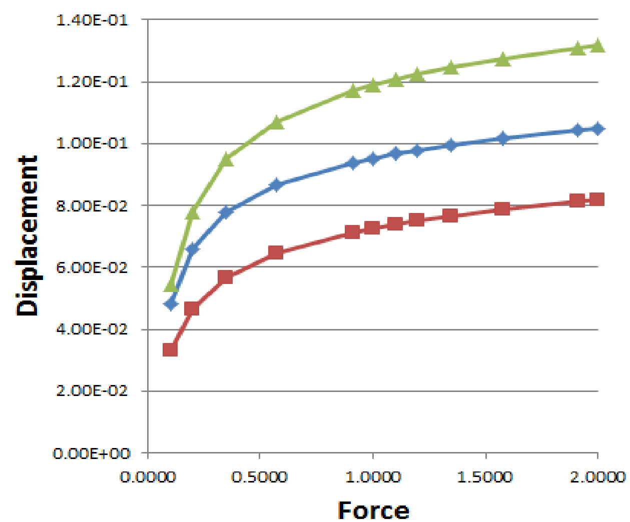
Axial load





Horizontal load





Material parameters were calibrated to obtain realistic force displacements

1st Order Ogden parameters:

- miu = 5.0E-4 alpha = 150
- miu = 3.5E-3 alpha = 150
- miu = 5.E-04 alpha = 120

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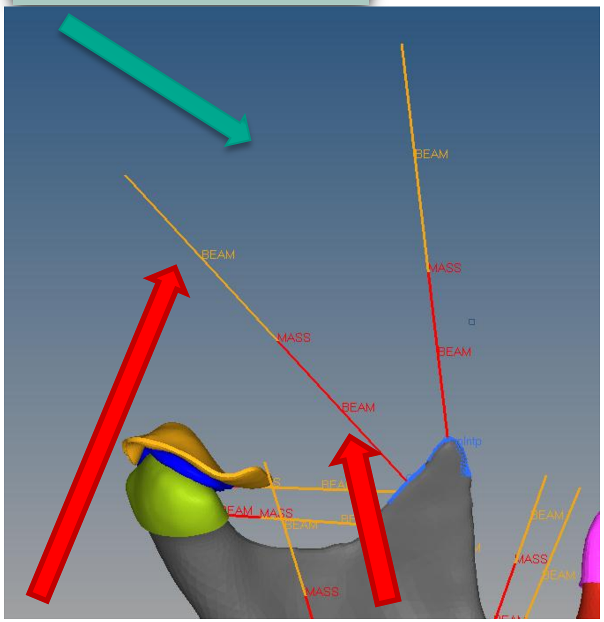
Muscle forces

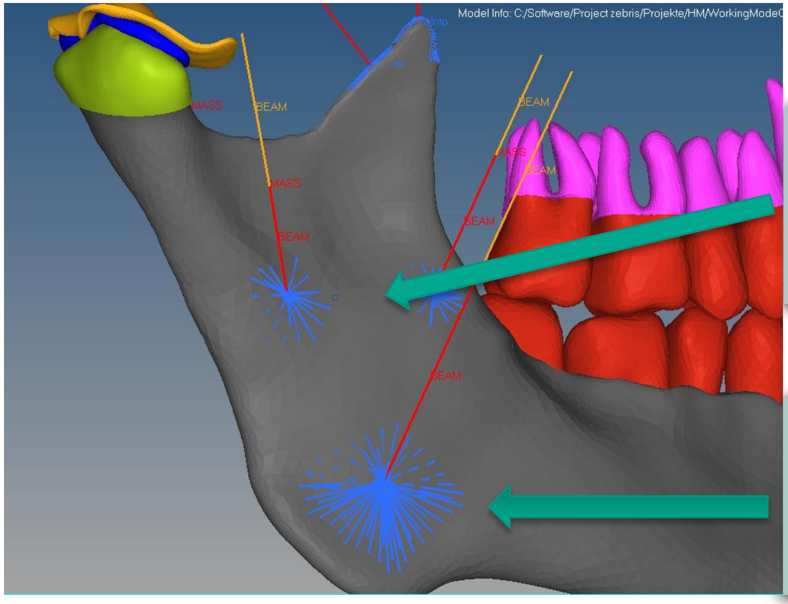
Temporalis



Fiber
(Hill muscle model)

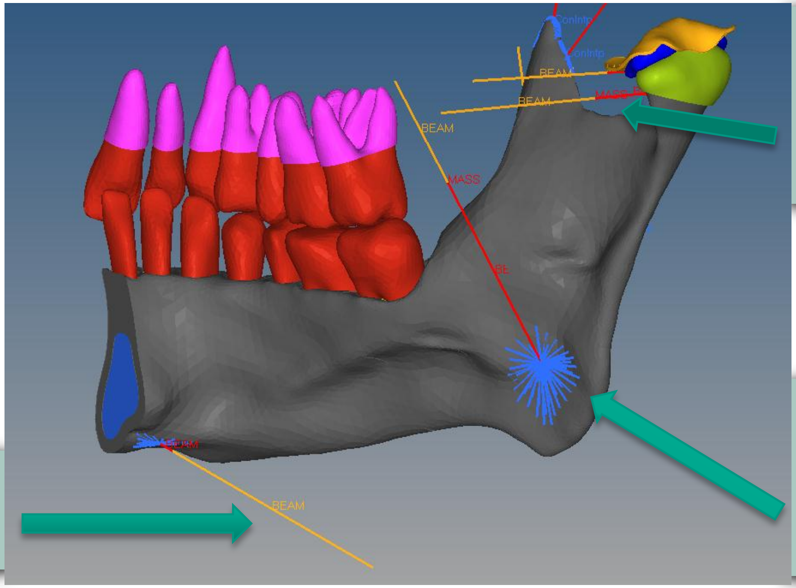
Tendon
(Inextensible wire)

Digastricus



Deep masseter

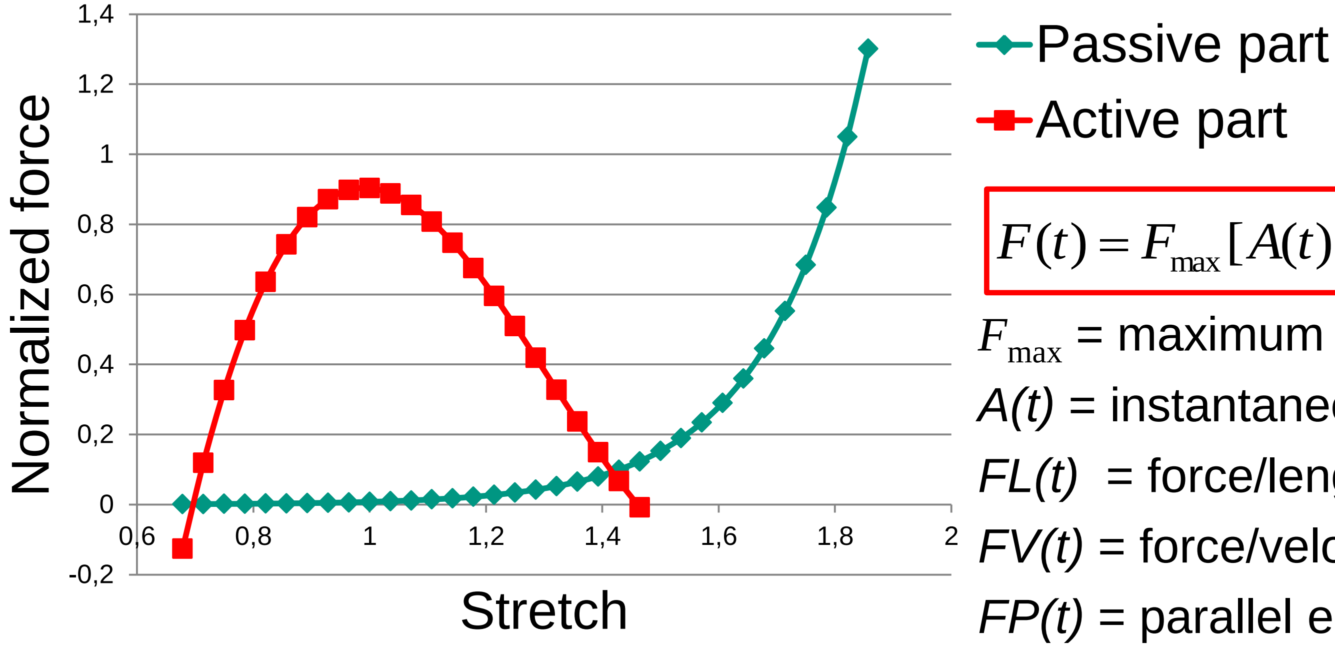
Superficial masseter



Lateral pterygoid

Medial pterygoid

Muscle forces



$$F(t) = F_{max}[A(t)FL(t)FV(t) + FP(t)]$$

F_{max} = maximum muscle force

A(t) = instantaneous activation level

FL(t) = force/length factor

FV(t) = force/velocity factor

FP(t) = parallel elastic element factor

Force-length characteristics of the muscle

$Ls(t)$ = Sarcomere length

Active → $$FL = 0.4128Ls(t)^3 - 4.3957Ls(t)^2 + 14.8003Ls(t) - 15.0515$$

Passive → $$FP = 0.0014\exp\left\{6\frac{Ls(t) - 2.73}{2.73}\right\}$$

*J.H Koolstra, T.M.G.J van Eijden (1997)

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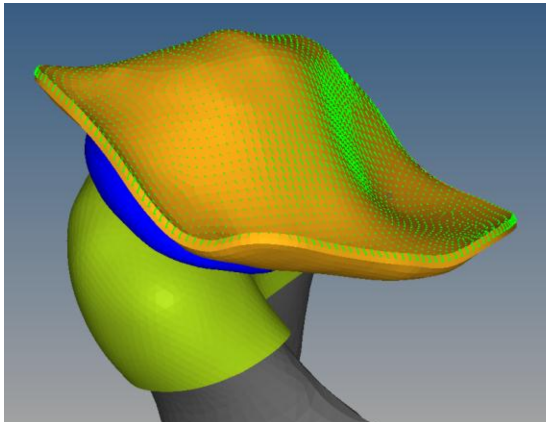
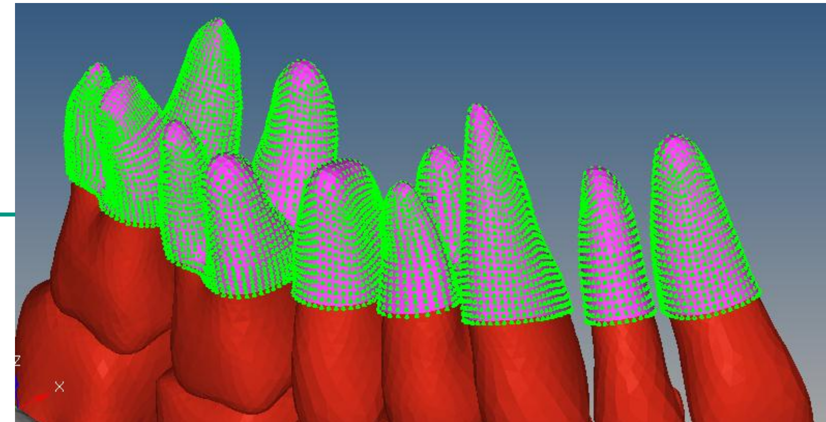
Constraints – fixed boundaries



Cartilage /Fossa

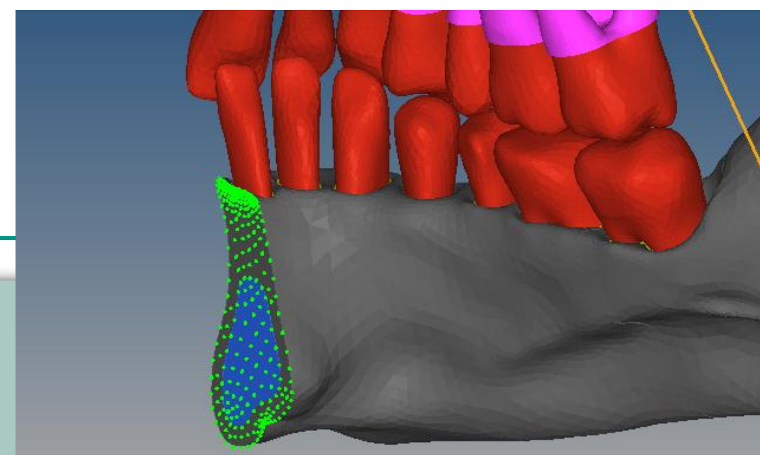
All degrees of freedom are constrained



PDL of the upper teeth/Maxilla

One degree of freedom is constrained

Symmetric model



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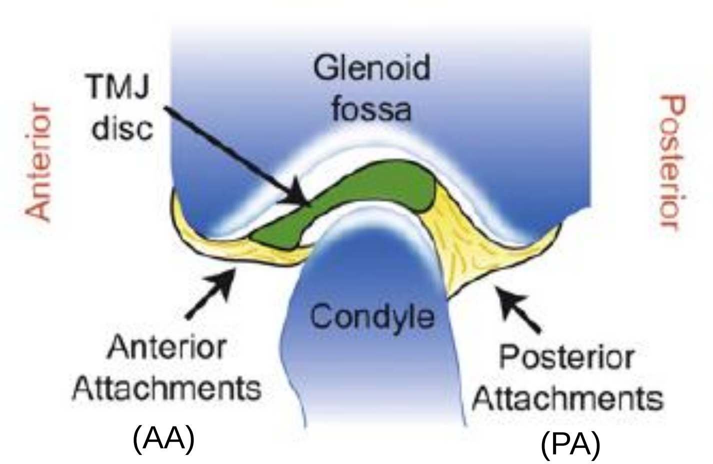
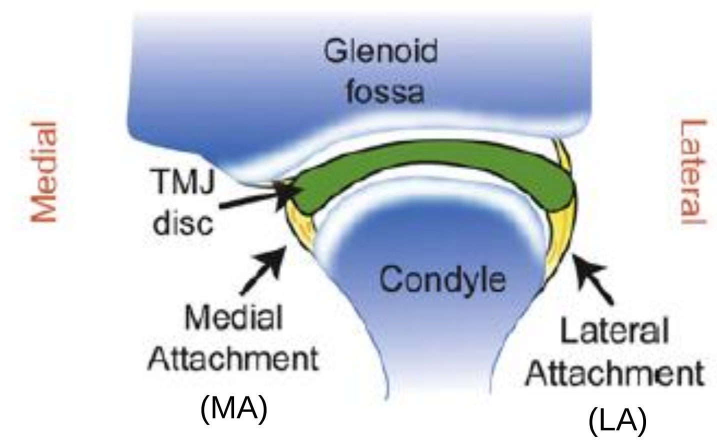
Temporomandibular joint - function

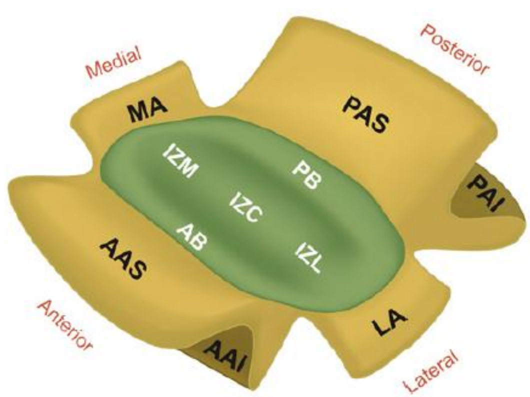
Sagittal View*



Coronal View*



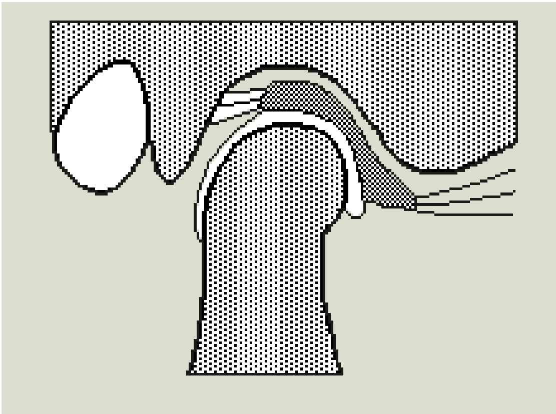
Disc and Attachments*

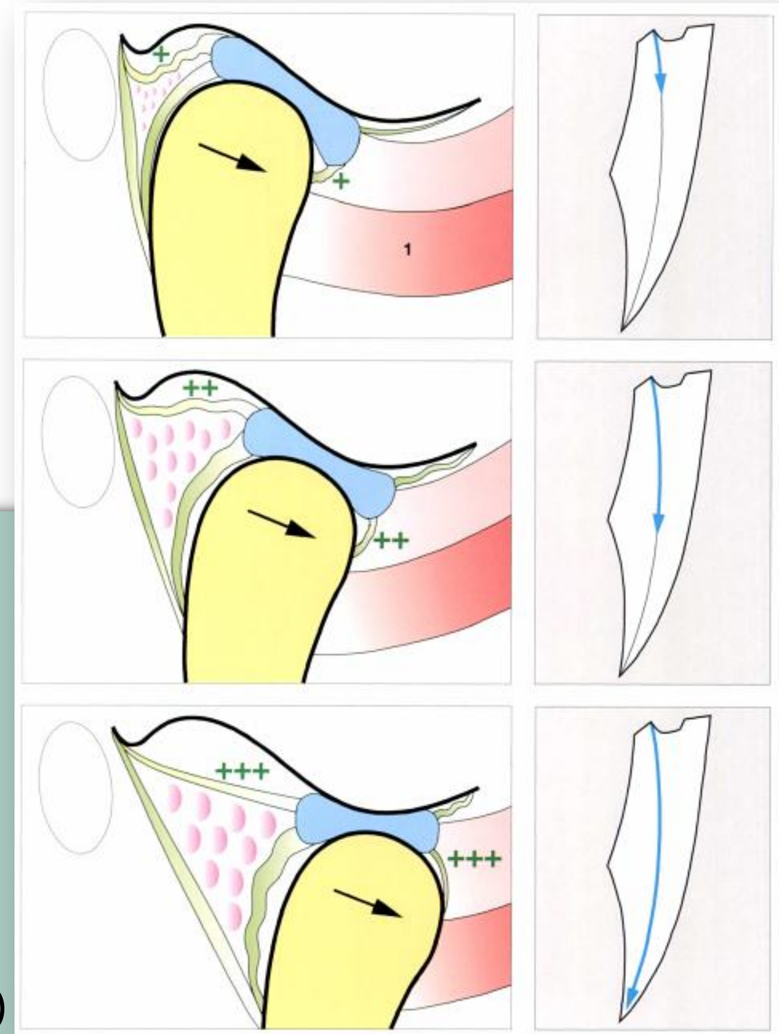


Vincent P. Willard (2003)

Attachments of the capsule keep the disc attached to the fossa and the condyle

Temporomandibular joint - motion





"Initial phase of an opening movement is primarily a rotation that always progresses with a translational component."

Color atlas of dental medicine:

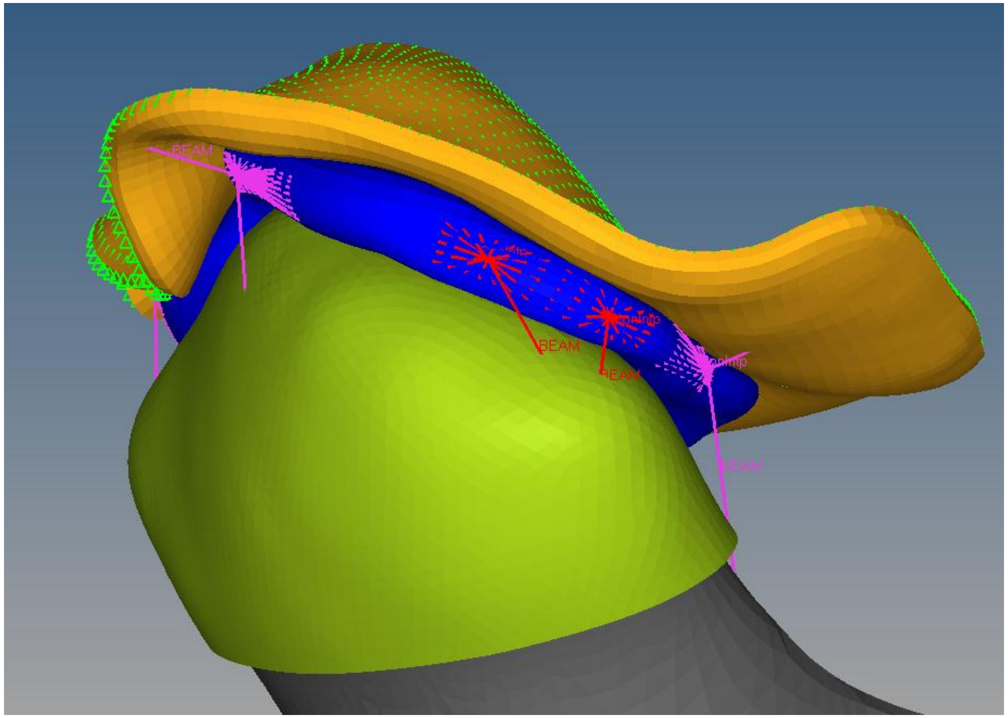
TMJ Disorders and Orofacial Pain (2002)

Temporomandibular joint

- Joint capsule is not visible in the CT scan
- Geometry is too complex to derive from literature
- Experimental data* of retrodiscal tissue: uniaxial tests only

↓

Attachment tissue modeled with trusses



*Tanaka E. et al. (2003)

Results - Opening

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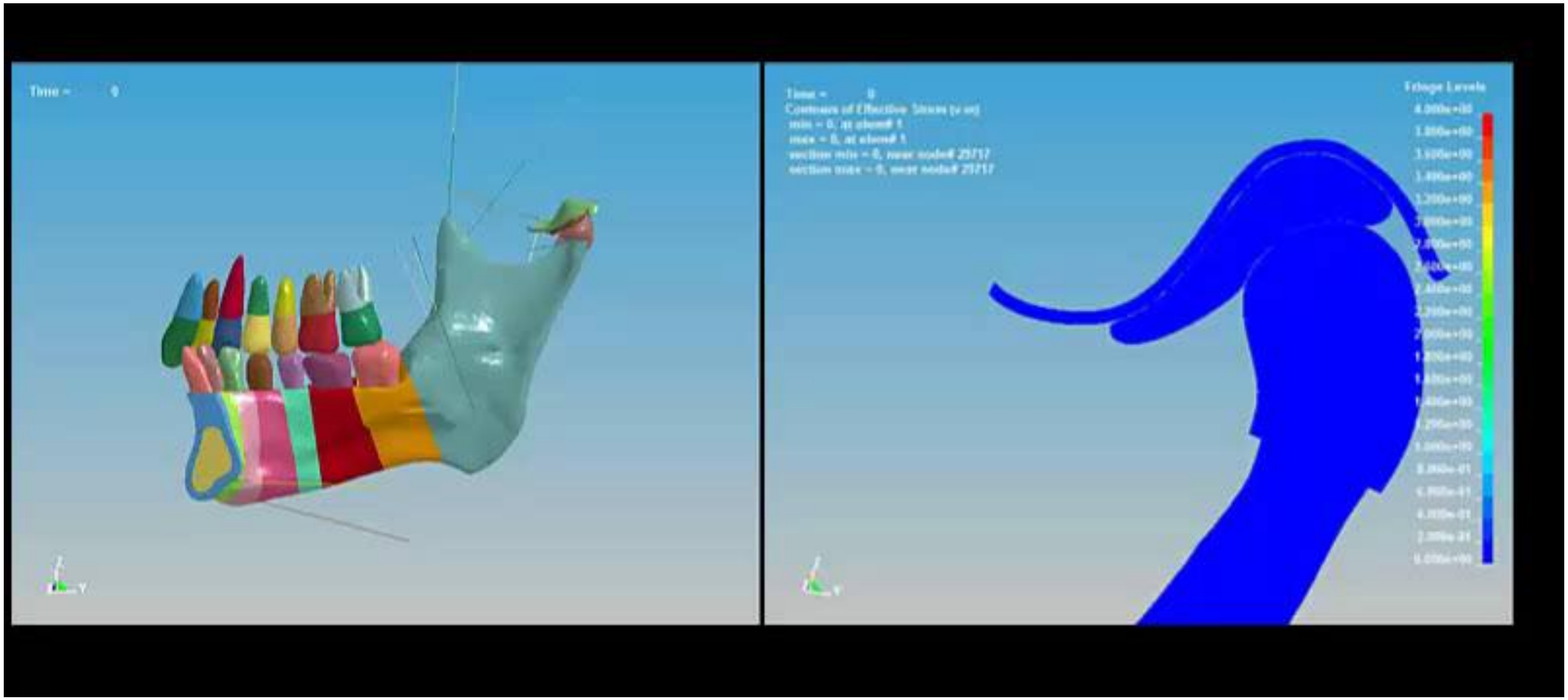

Opening gap of 30 mm limited by lack of movement of the hyoid bone.
Great effort was taken to obtain a realistic motion

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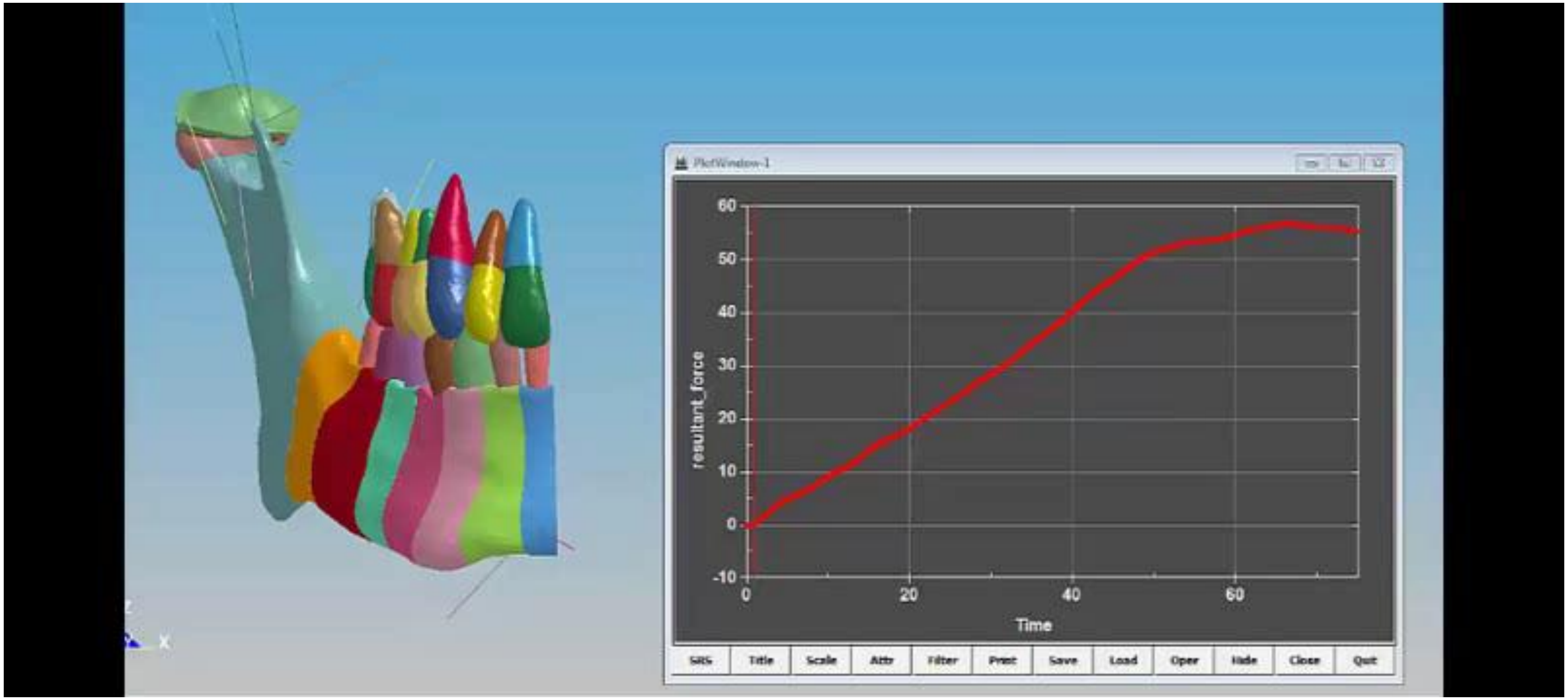
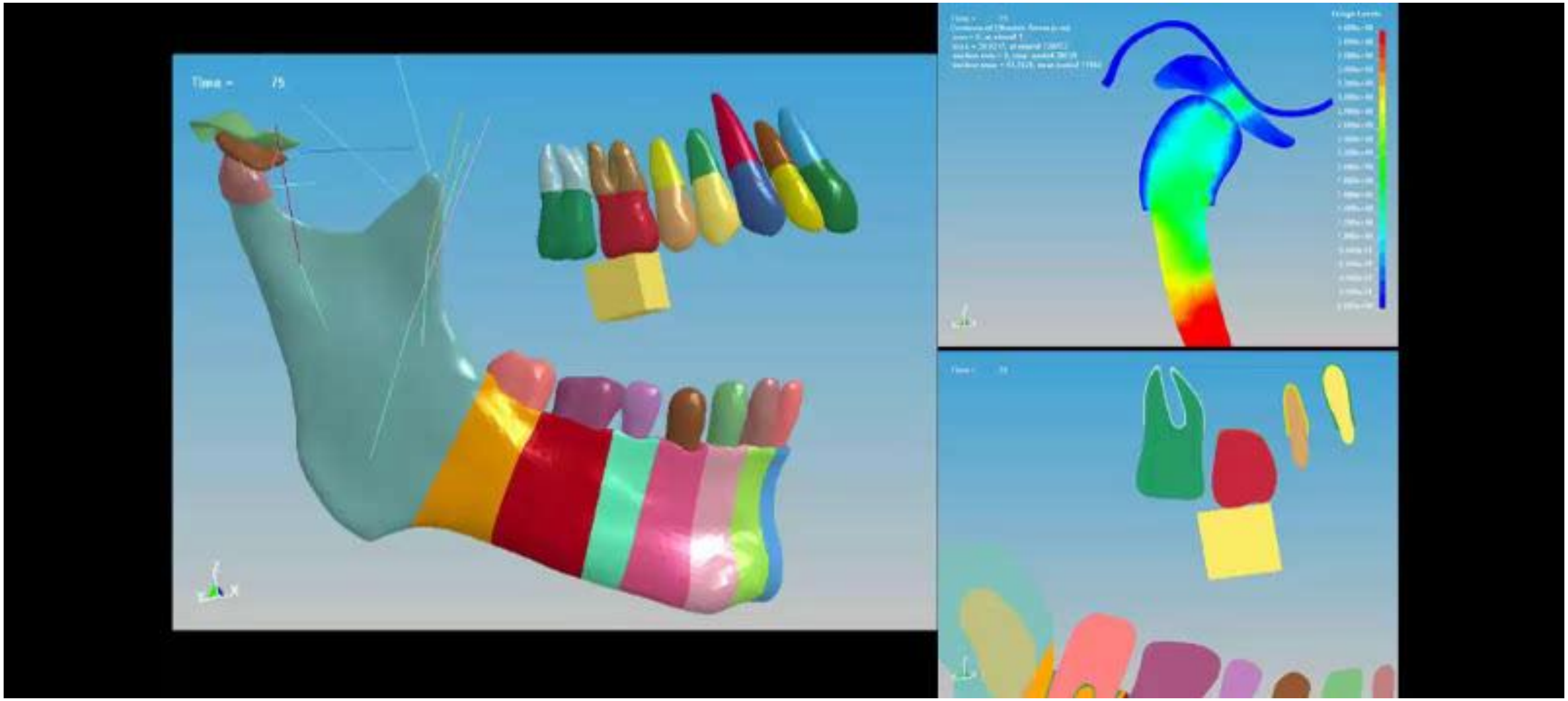
Results – Jaw forces during opening



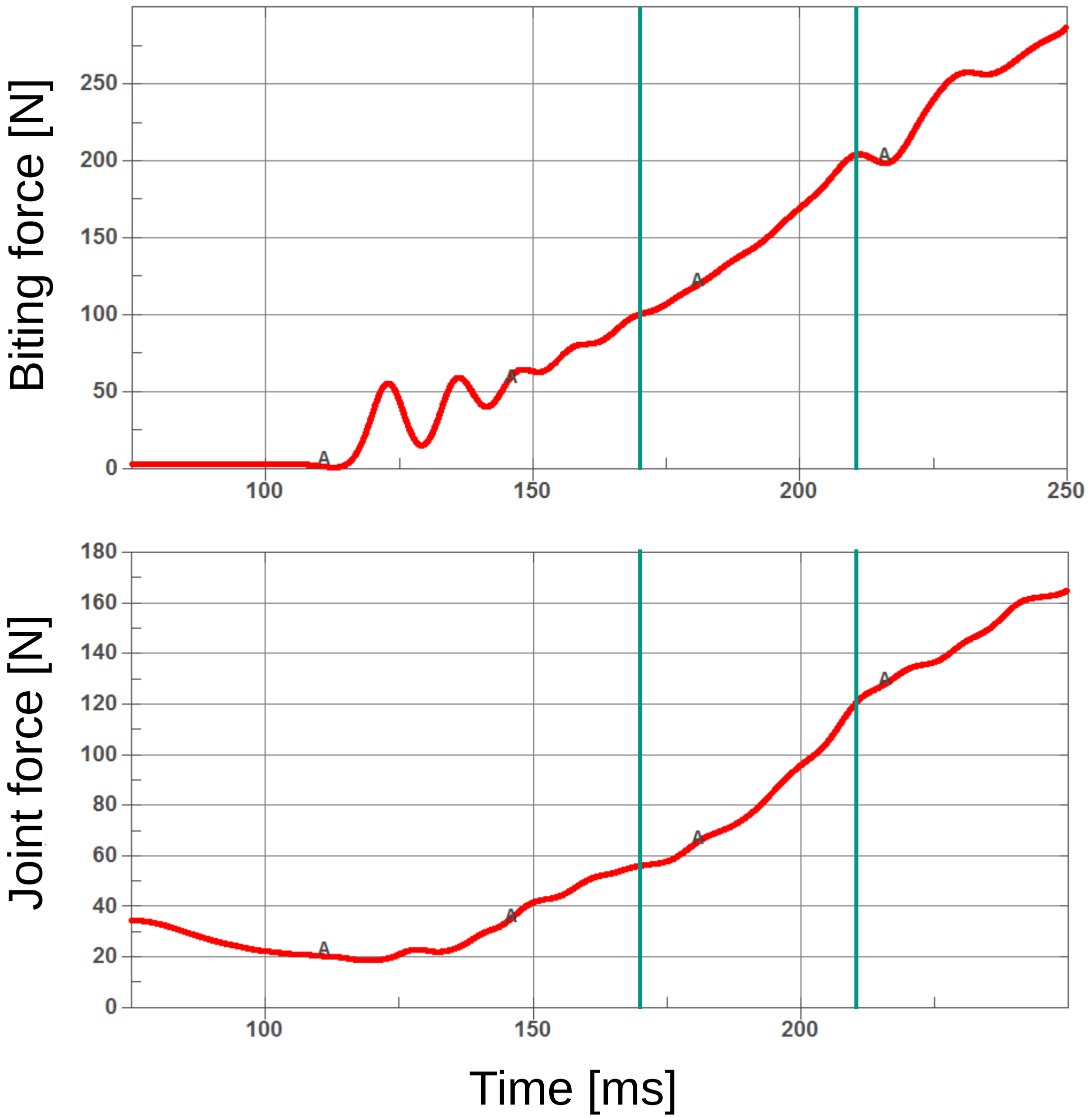
Forces in the joint match those found in the literature

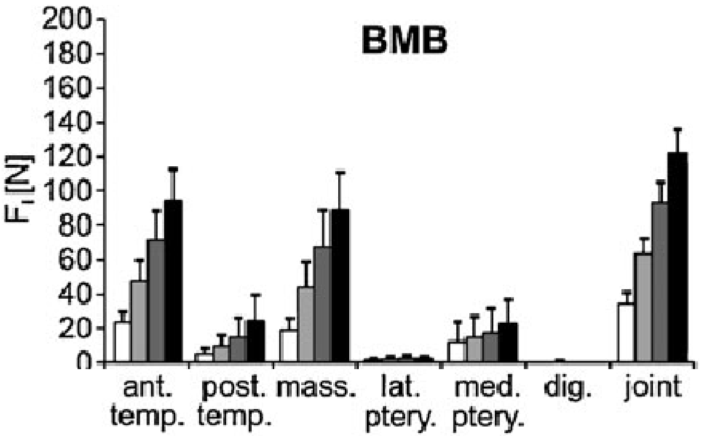
Results – biting a test bolus



Muscle activation and resulting biting and joint forces
in agreement with Rues et al. (2009)

Results – biting a test bolus - validation





*Forces under Bilateral Molar Biting (BMB)
Rues et al. (2009)

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Results – biting a test bolus (asymmetric)

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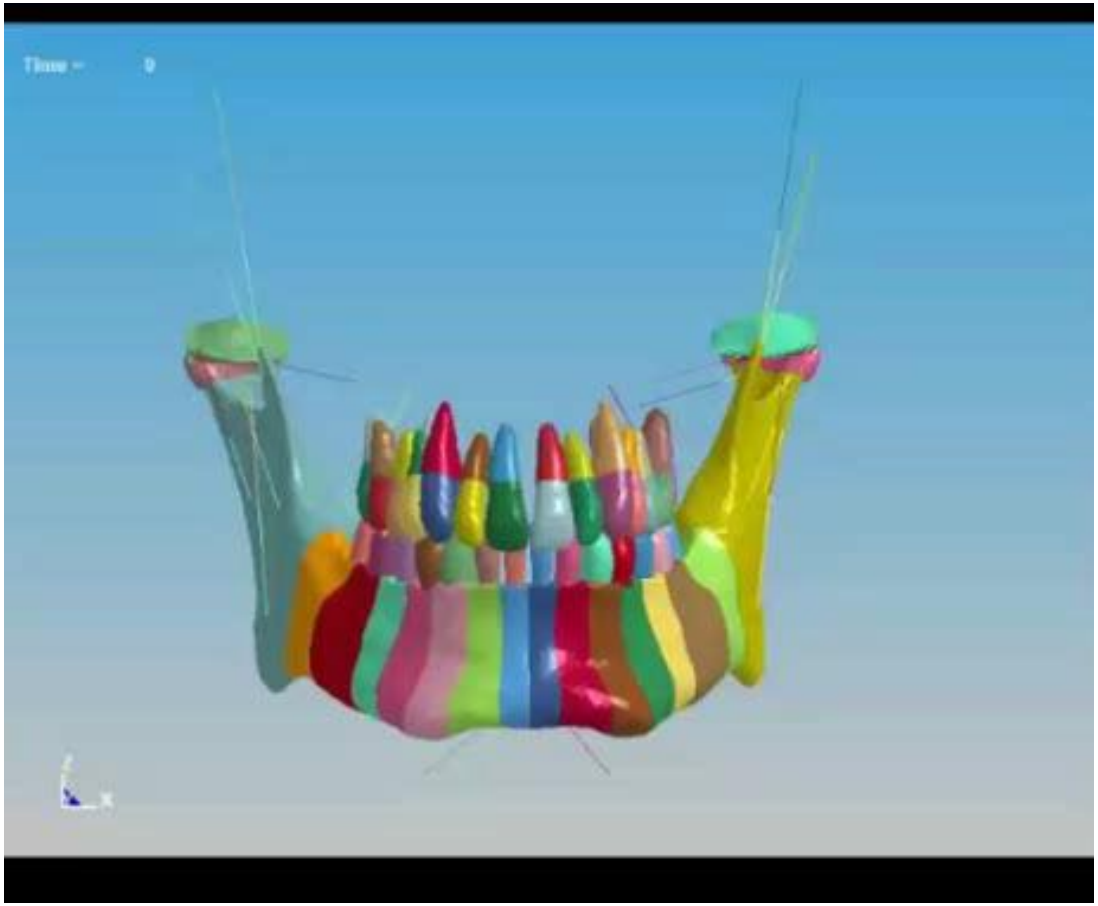


Muscle activation and resulting biting and joint forces **again in agreement** with Rues et al. (2009)

Summary

- Model shows realistic behavior during opening and closing motions
- Stresses and reaction forces show good agreement with previous works found in the literature
- Computational requirements:

#CPU	Problem time [ms]	# Elements	#DOF	Computational time [h]
16	180	920.000	582.000	30
32	180	920.000	582.000	22
16	180	1.840.000	1.164.000	60

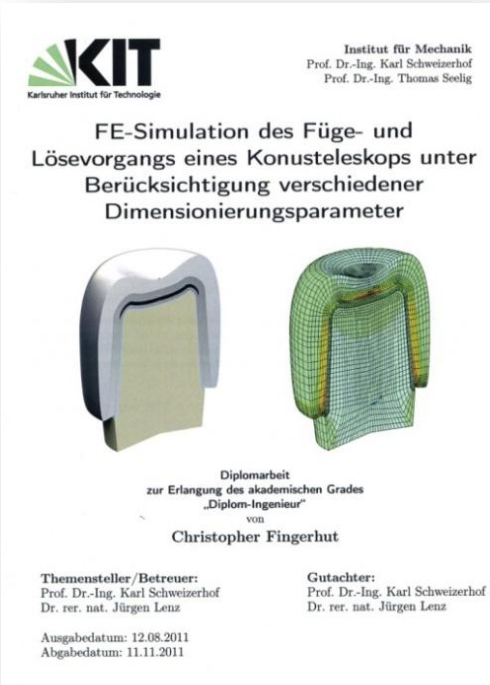
Current model simplifications / limitations
(Not essential for this project)

- Anisotropic behavior of the disc not implemented
- Capsule and ligaments not modeled
- Hyoid bone remains in a fixed position during jaw movement
- Problem time: 250 ms → Natural time: 500 ms

RESEARCH GROUP BIOMECHANICS

THANK YOU FOR YOUR ATTENTION

Previous work by the Institute of Mechanics on teeth and jaw modeling



Karlsruher Institut für Technologie

Institut für Mechanik
Prof. Dr.-Ing. Karl Schweizerhof
Prof. Dr.-Ing. Thomas Seelig

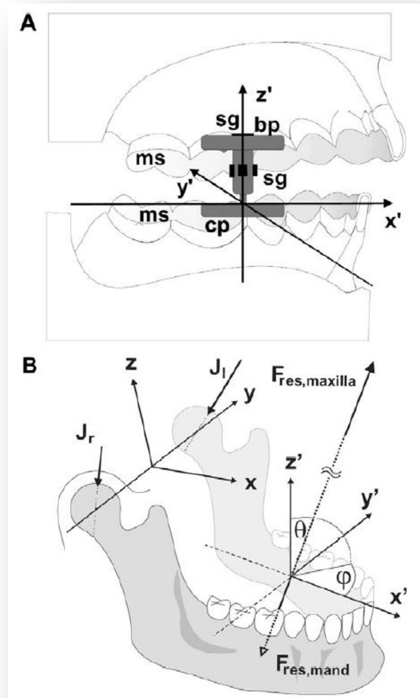
FE-Simulation des Füge- und Lösevorgangs eines Konusteleskops unter Berücksichtigung verschiedener Dimensionierungsparameter

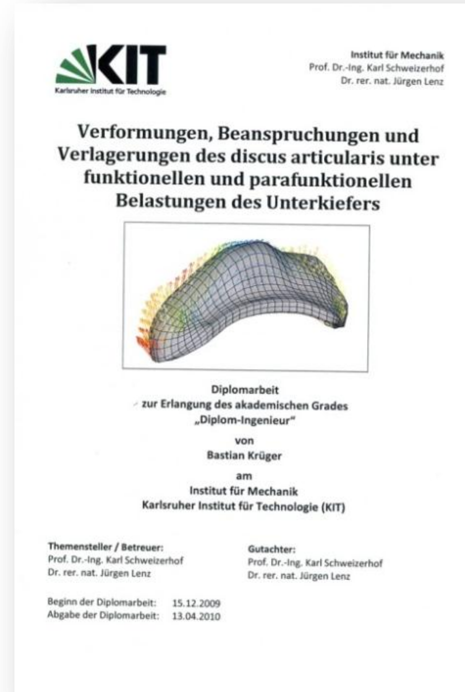
Diplomarbeit
zur Erlangung des akademischen Grades
„Diplom-Ingenieur"
von
Christopher Fingerhut

Themensteller/Betreuer:
Prof. Dr.-Ing. Karl Schweizerhof
Dr. rer. nat. Jürgen Lenz

Gutachter:
Prof. Dr.-Ing. Karl Schweizerhof
Dr. rer. nat. Jürgen Lenz

Ausgabedatum: 12.08.2011
Abgabedatum: 11.11.2011





Karlsruher Institut für Technologie

Institut für Mechanik
Prof. Dr.-Ing. Karl Schweizerhof
Dr. rer. nat. Jürgen Lenz

Verformungen, Beanspruchungen und Verlagerungen des discus articularis unter funktionellen und parafunktionellen Belastungen des Unterkiefers

Diplomarbeit
zur Erlangung des akademischen Grades
„Diplom-Ingenieur"
von
Bastian Krüger
am
Institut für Mechanik
Karlsruher Institut für Technologie (KIT)

Themensteller / Betreuer:
Prof. Dr.-Ing. Karl Schweizerhof
Dr. rer. nat. Jürgen Lenz

Gutachter:
Prof. Dr.-Ing. Karl Schweizerhof
Dr. rer. nat. Jürgen Lenz

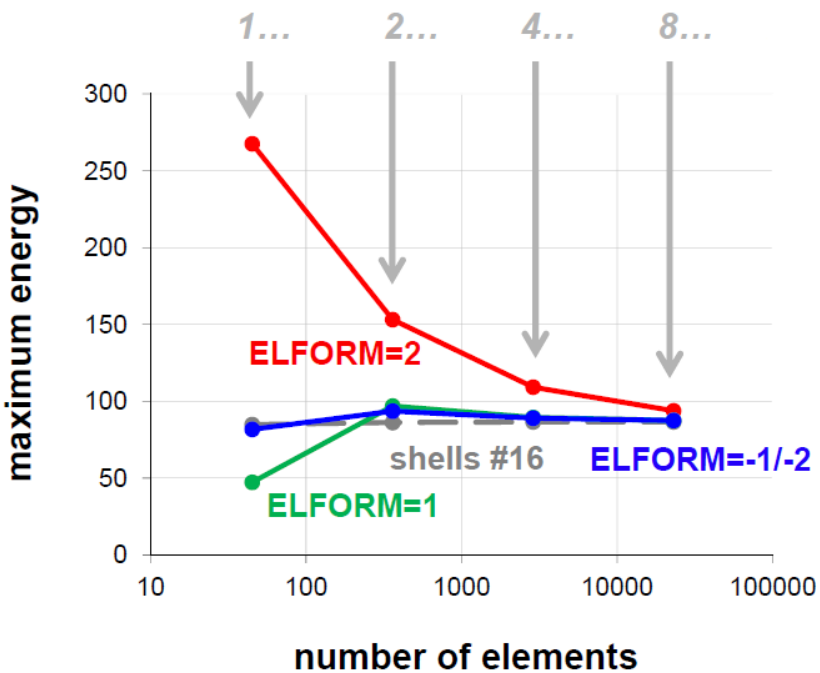
Beginn der Diplomarbeit: 15.12.2009
Abgabe der Diplomarbeit: 13.04.2010

- Magnitude of forces fundamental to determine optimal muscle activation
- Existing TMJ used as an initial guiding model

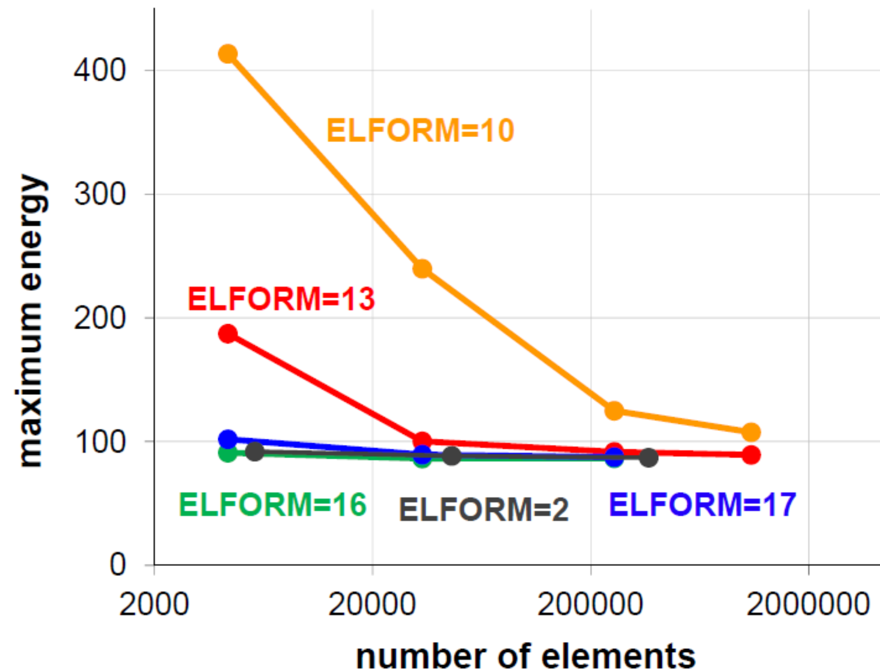
Model discretization

Software: LS-DYNA R6.1 (LSTC, USA, 2013)

Hexahedral elements



Tetrahedral elements



- Good convergence with types 1,-1,-2
- Type 1 most efficient

- Bad convergence of type 10 (stiff behavior)
- Better convergence with types 13,16,17

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