Modelling of the patient-specific shape variation of the human mandible with Statistics on Structures

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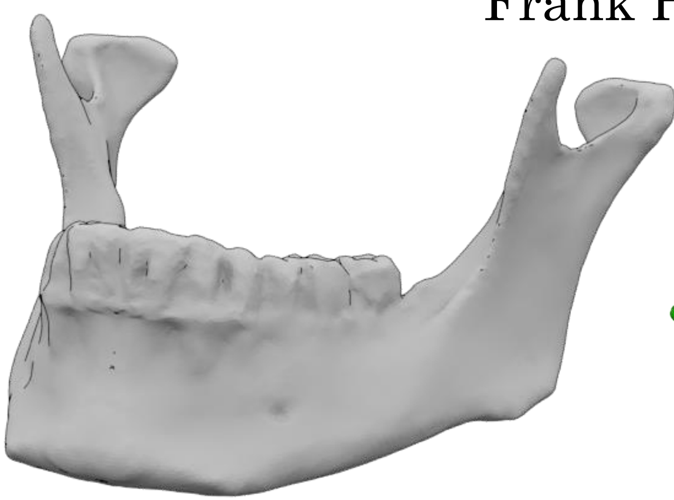

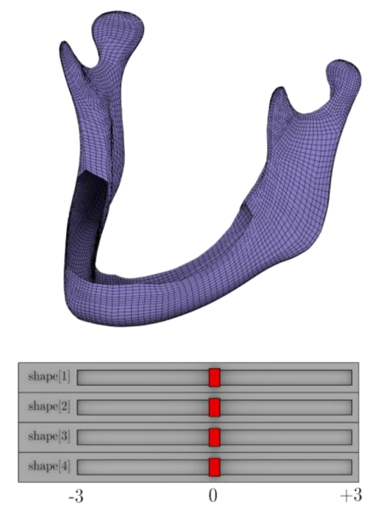

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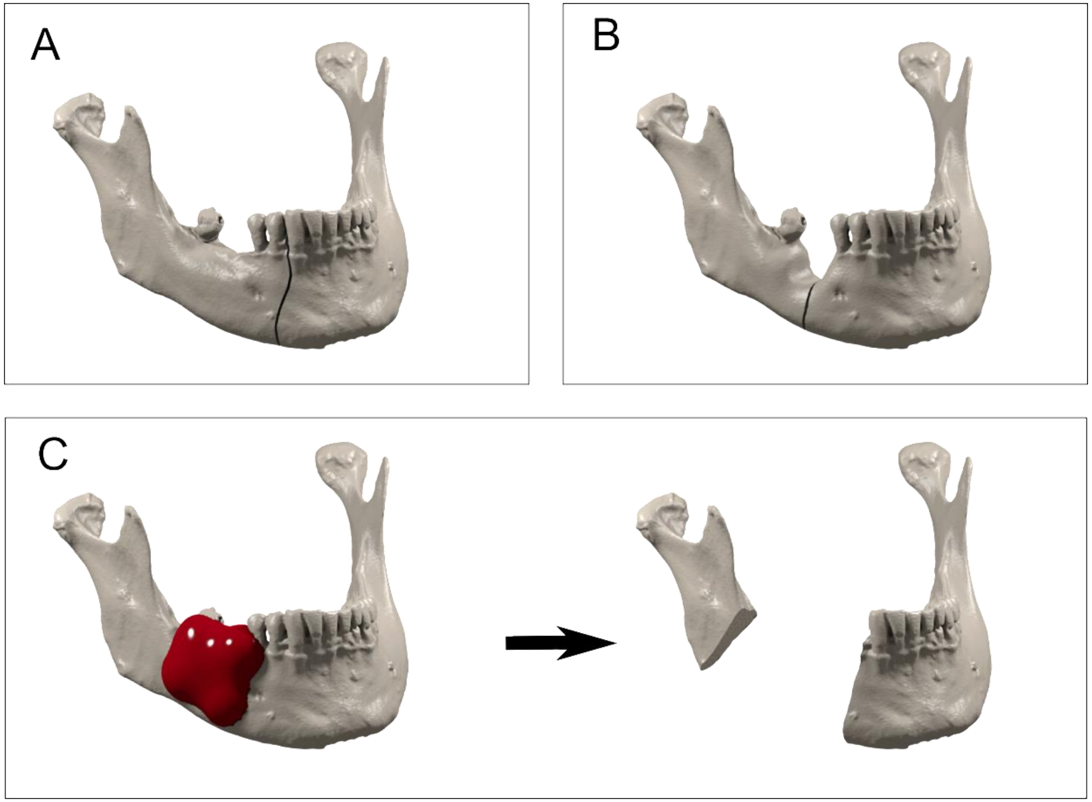
Indications for osteosynthesis treatments



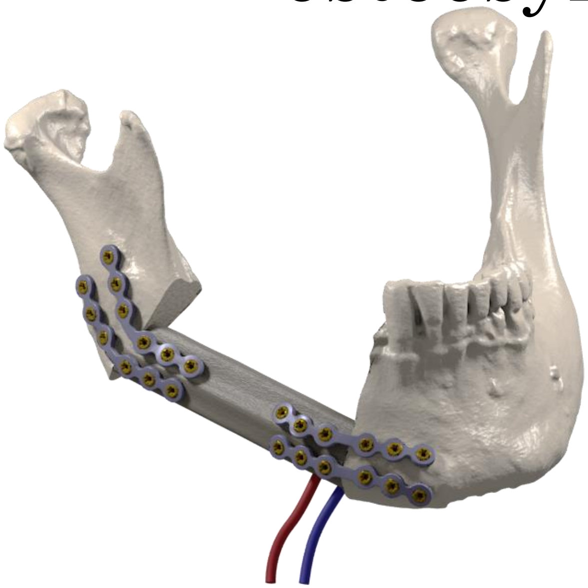
- Mandible fractures (A) are stabilized with small osteosynthesis plates
- Cystic bone atrophy (B) or tumors (C) make bone removal necessary

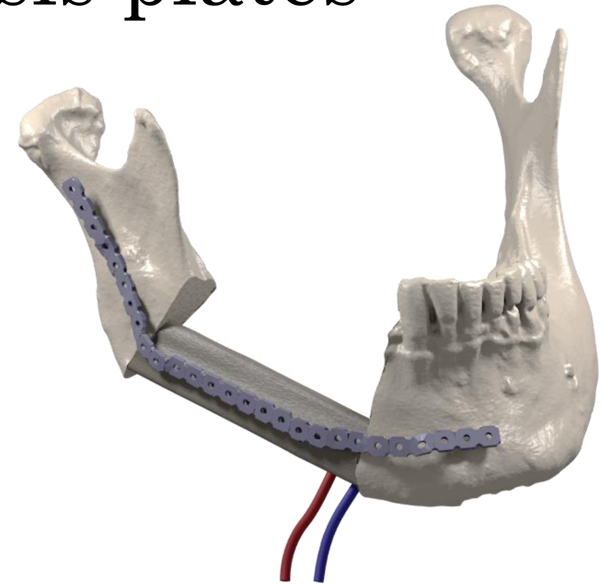
Research questions:

-> how to dimension optimal osteosynthesis plates (WOST 2013)

-> how to shape the missing part (e. g. for 3-D printing of bone replacements)

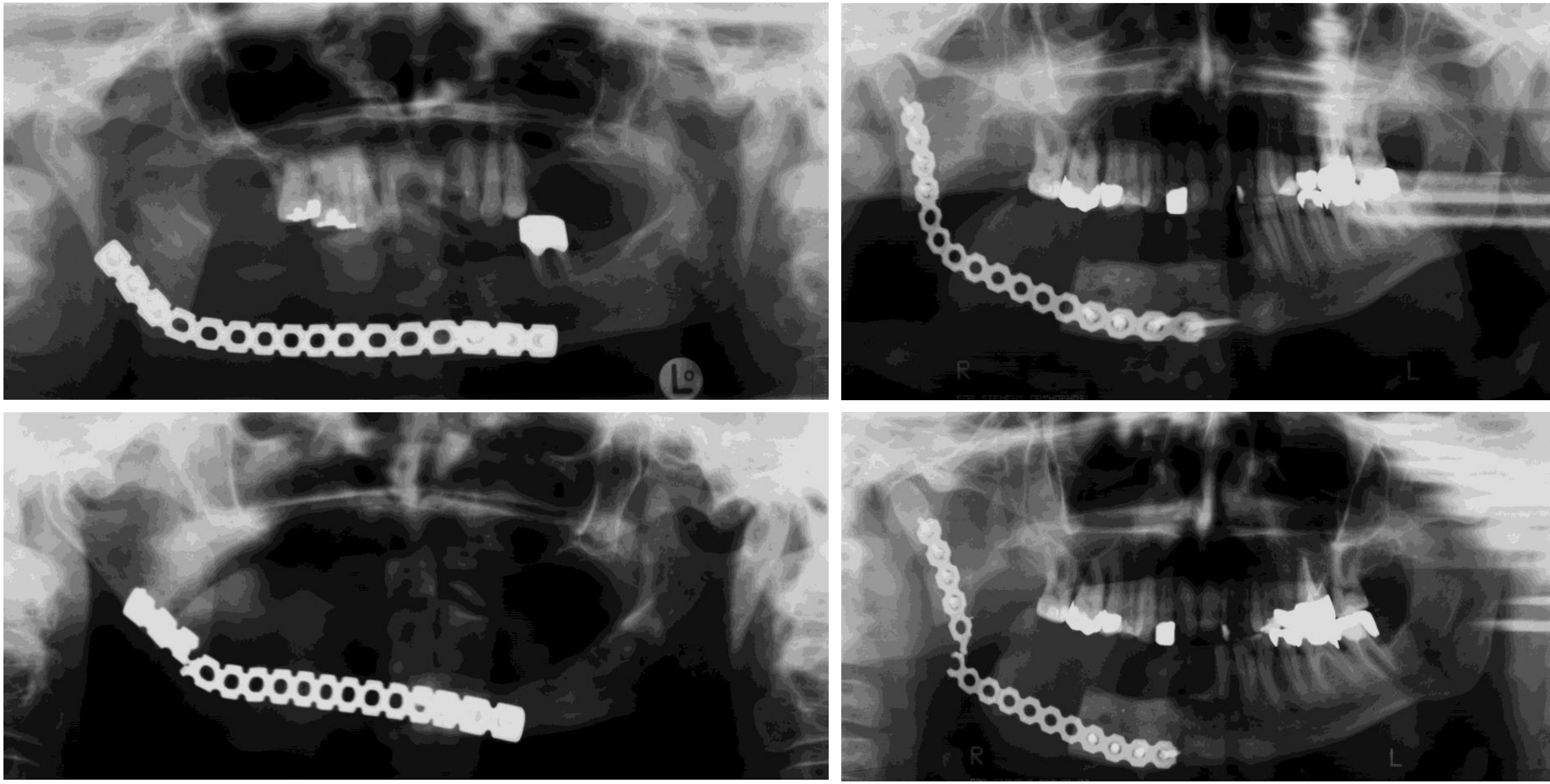
Reconstruction with bone transplants and osteosynthesis plates





- Reconstruction plates are difficult to adapt to individual shapes
- Plates are bent inter-operatively in a tedious and time consuming procedure
- Plastic deformations are weakening the material and may cause plate fractures when chewing forces are acting
- Reconstruction with autologous bone transplants cause defects elsewhere
- Transplant bone shapes are predefined and don‘t match the mandible shape

Clinical problems: plate factures



Could in future the bone replacement be 3-D printed with synthetic biomaterials?

What shapes would be required to fill the defect area in an optimal way?

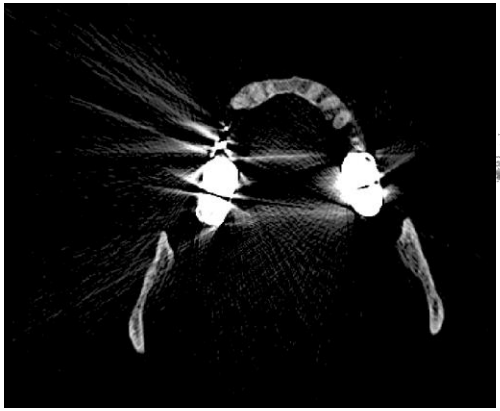
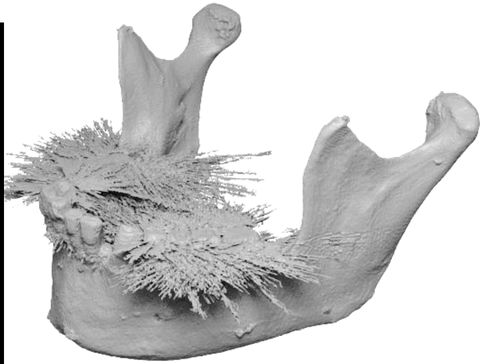
Problem Setting:

explicit variability of the shape of the mandible bone in between different patients

- Complex shape of the mandible bone
  - Several parameters are necessary to describe its shape sufficiently
  - Geometric evaluations are more difficult than at the simpler shaped tube bones in orthopedics
  - Evaluations should be standardized and reproducible
    - large data sets make automation necessary

Data base of the study presented here: 63 human mandibles

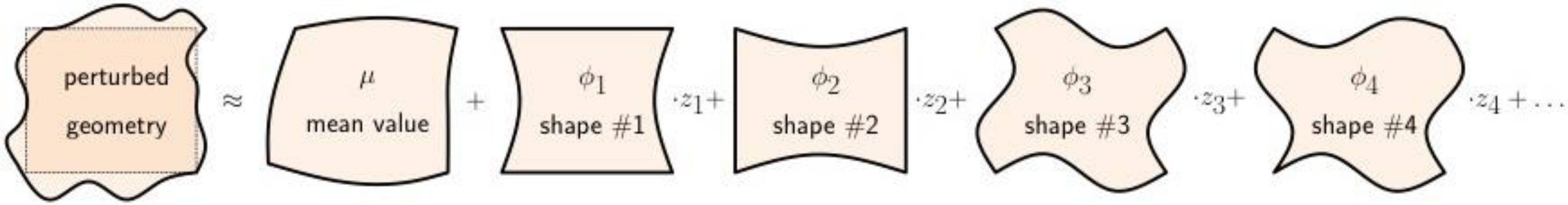


- Volumetric images of CT scans
  - Resolution 0,35 x 0,35 x 0,33 mm
- Semiautomatic segmentation
  - Artifacts due to metallic structures need to be removed manually
- Triangulated surface data of the mandible bone
  - 63 data sets in the present study

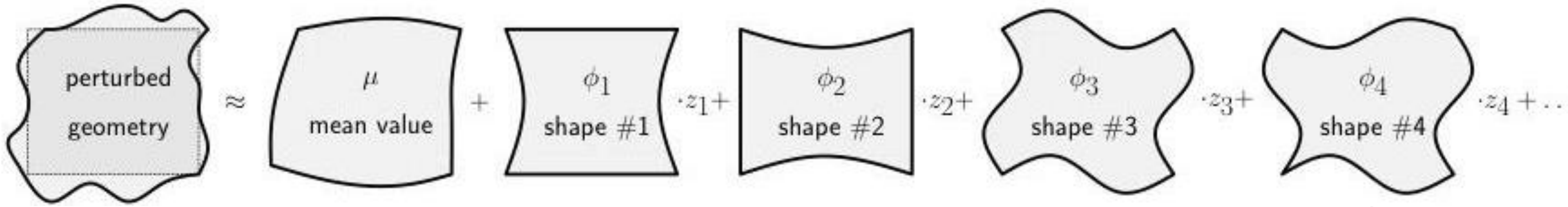
Random field model

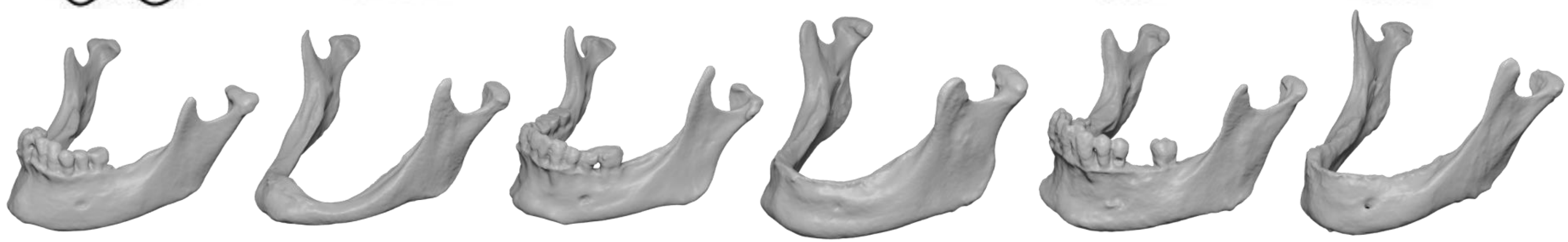
- Approximate a random design with
  - mean value +
  - linear combination of deterministic "scatter shapes" multiplied with random coefficients ("amplitudes")



- Accurately resembles
  - Statistical moments (mean, standard deviation…)
  - Spatial correlations (anisotropic, inhomogeneous…)
- Geometry variations defined by x,y,z vector field
- x,y,z considered in cross-correlation (correlation among different locations in space and - at the same time - among different directions)

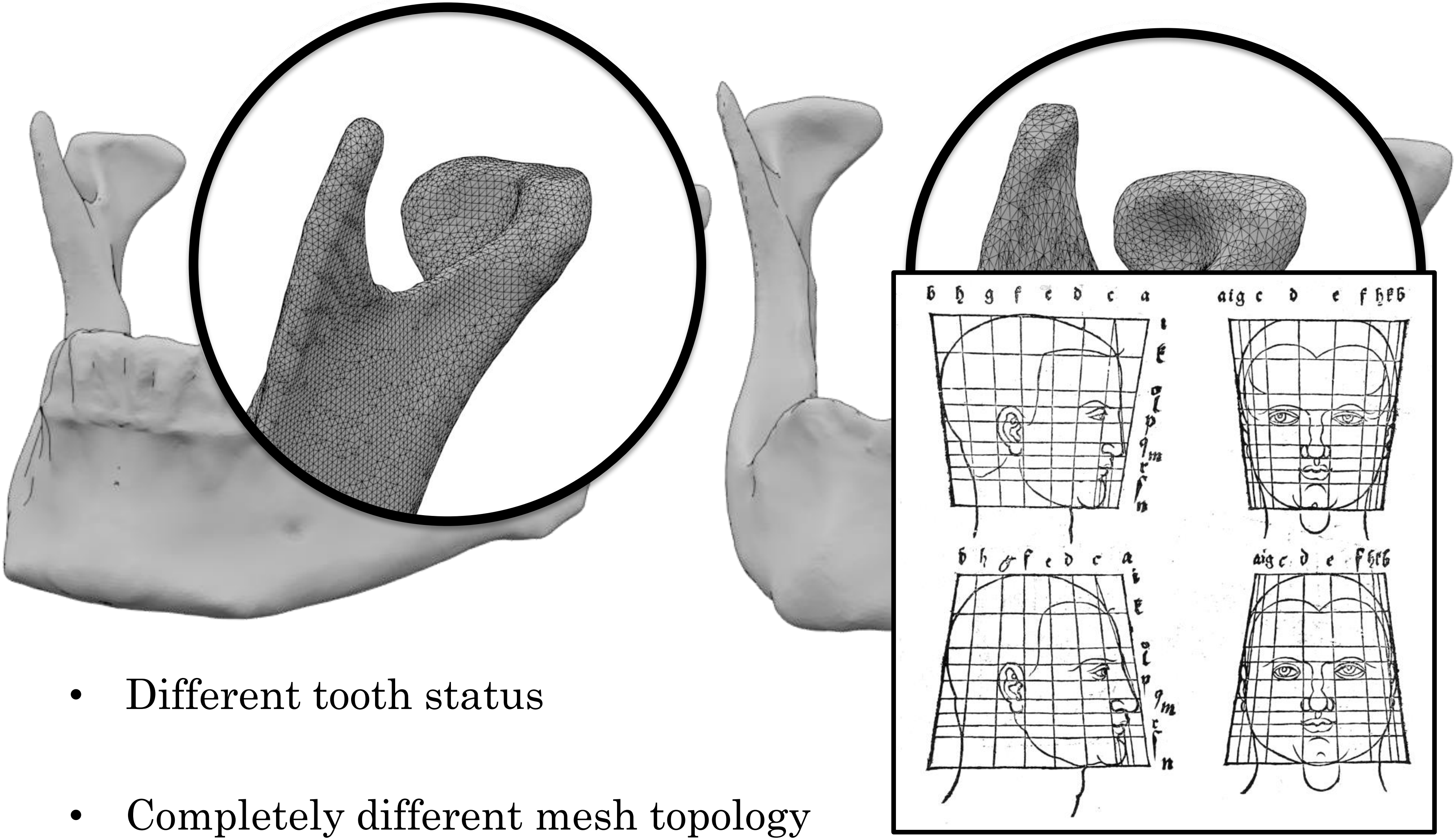
Relation of Random Field Models to Human Data





How can these geometries be evaluated with Statistics on Structures?

Challenge: no consistent mesh topology

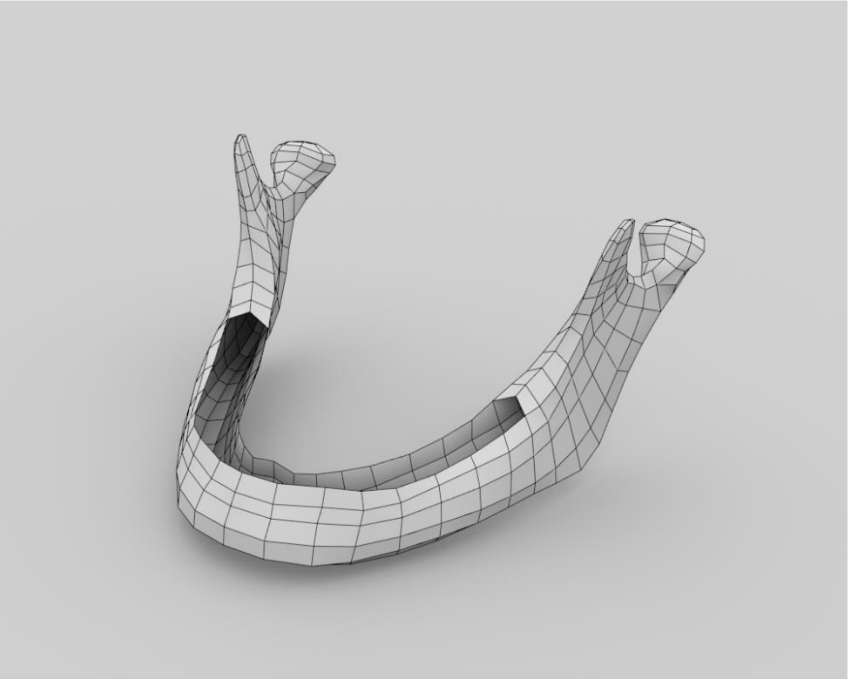


- Different tooth status
- Completely different mesh topology

Standard mesh for mandible geometry

- Manually generated
  - According to mean values of a previous study (WOST 2013)

blender



- Coarse mesh
  - 555 Vertices
- Symmetrical shape
- Topological edge flow

Standard mesh for mandible geometry

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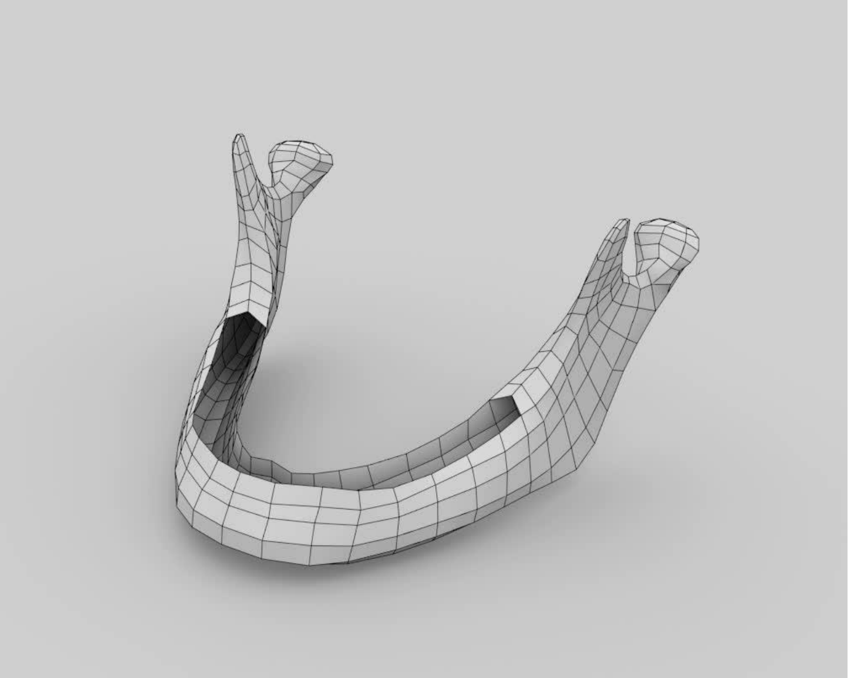
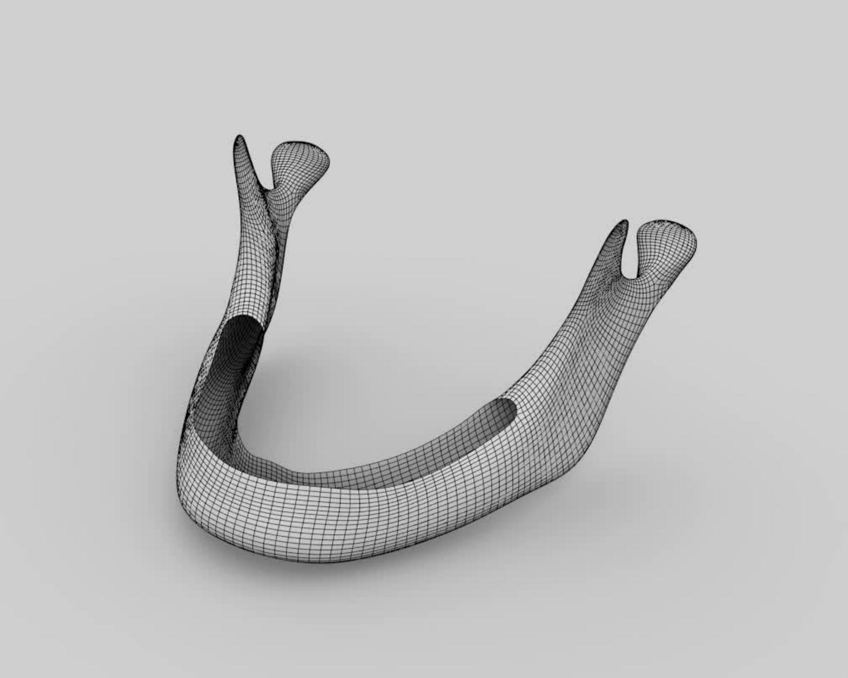


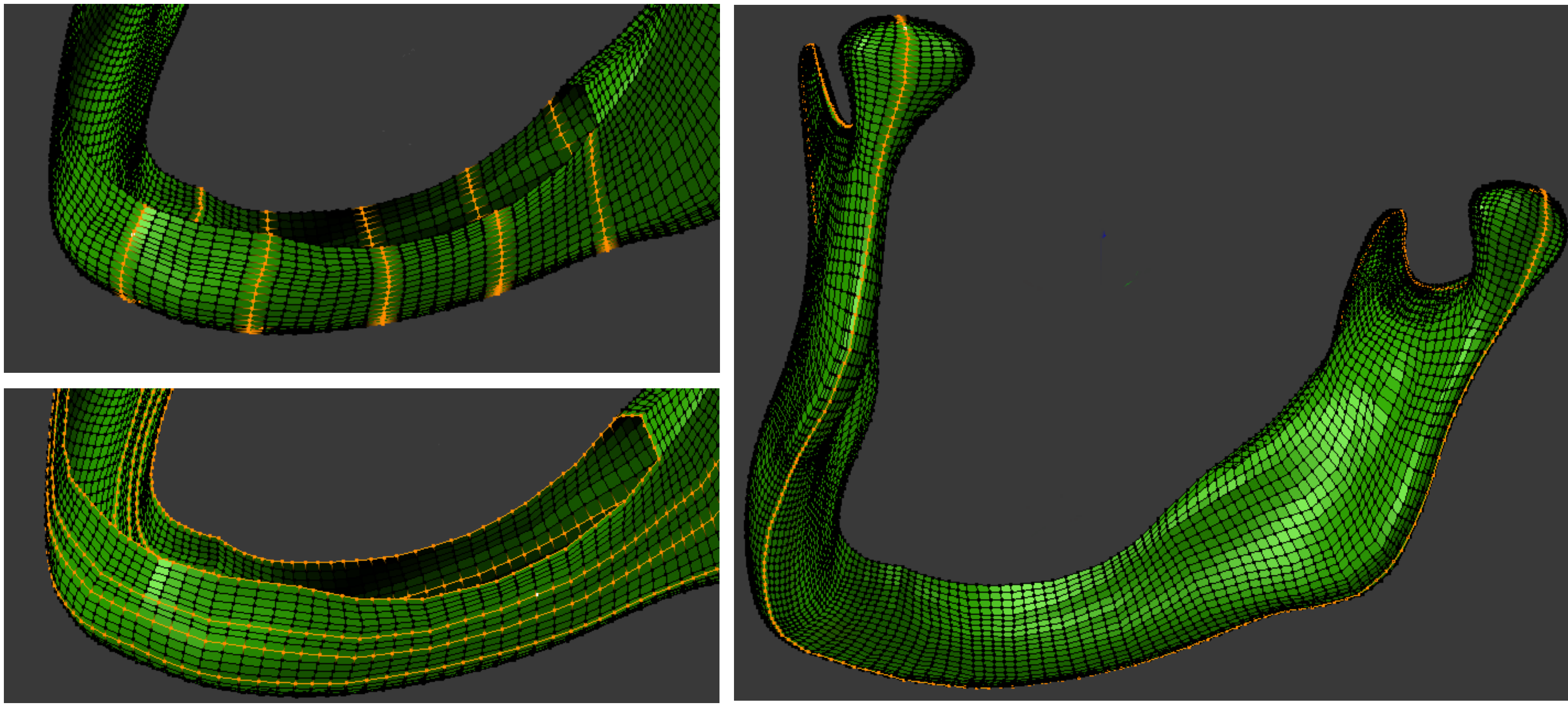
- Coarse mesh
  - 555 Vertices
- Symmetrical shape
- Topological edge flow

Standard mesh for mandible geometry

- Based on the coarse mesh
- Mesh refinement
  - ~ factor 16
  - 8649 Nodes
- Subsequent mesh projections towards segmented geometries
- Topological edge flow is conserved

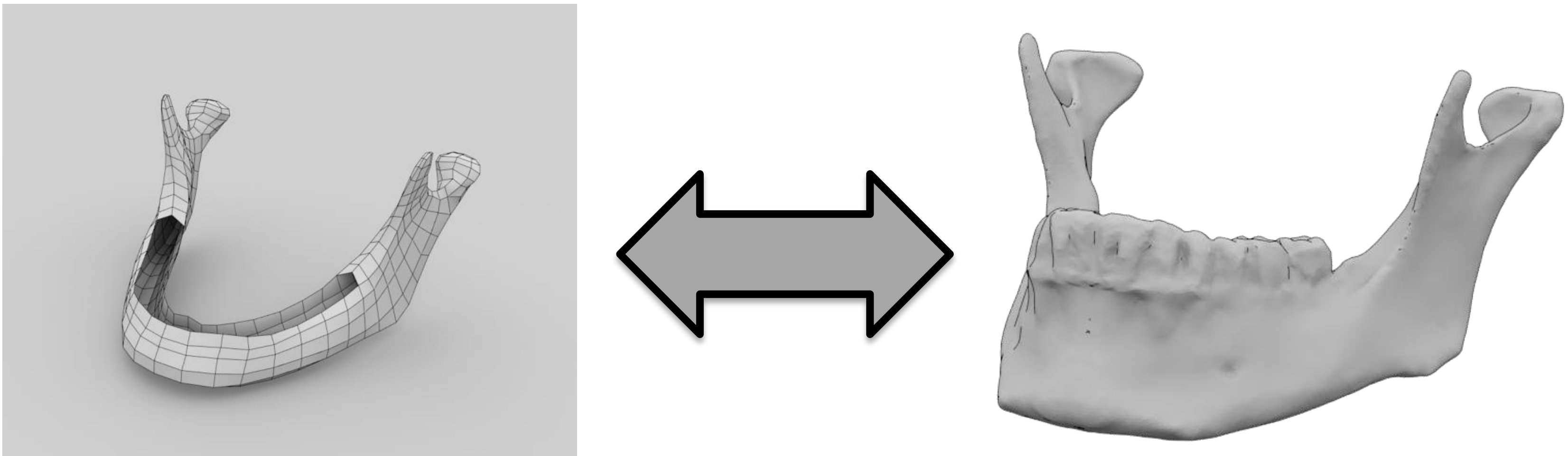


Topological edge flow



- Edge definition that follows anatomical shapes
- Important guidelines for surgeons
- Only feasible with quadrilaterals instead of triangles

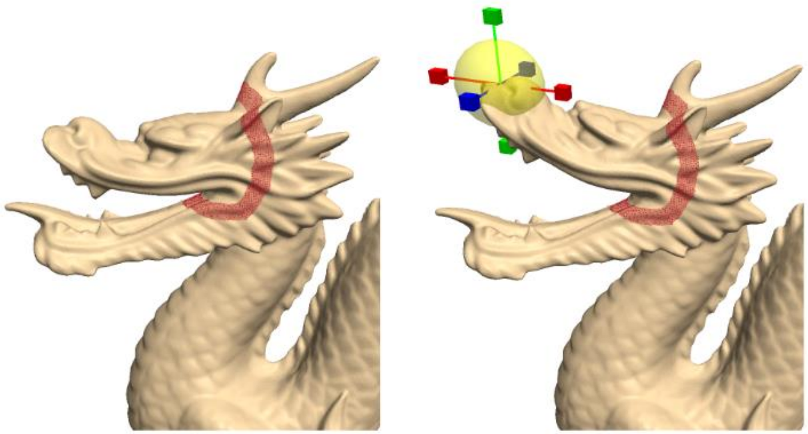
How can we adjust the standard shape to the individual mandibles?



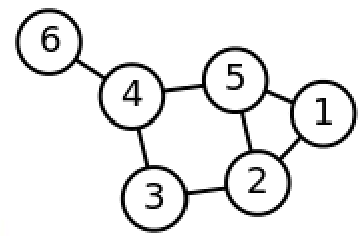
- Two step procedure:
  - geometry adjustment of coarse geometry
  - Iterative refinement and projection operations

Mesh Morphing with „Laplacian Surface Editing“

- Sorkine, Olga, et al. "Laplacian surface editing." *Proceedings of the 2004 Eurographics/ACM SIGGRAPH symposium on Geometry processing*. ACM, 2004.



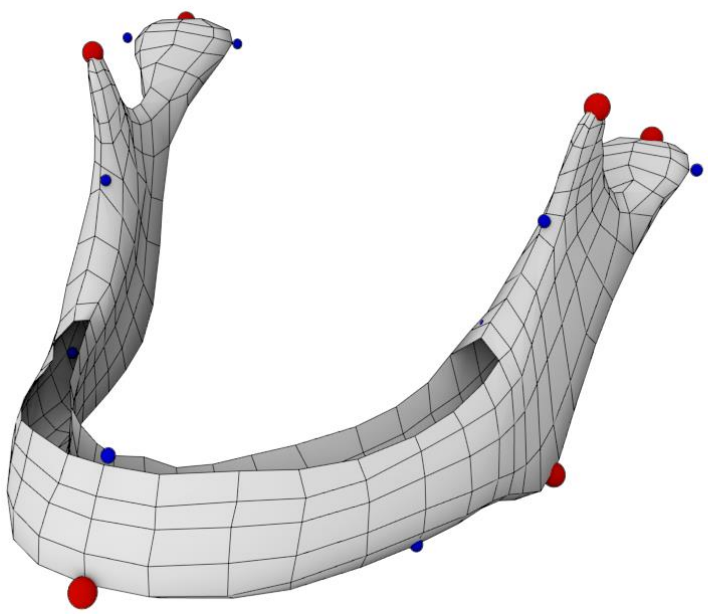
(a) (b)



$$\begin{pmatrix} 2 & -1 & 0 & 0 & -1 & 0 \\ -1 & 3 & -1 & 0 & -1 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 3 & -1 & -1 \\ -1 & -1 & 0 & -1 & 3 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \end{pmatrix}$$

- Morphing of mesh with consistent topology
- Allows modifications of fine meshes in real time
- Small features are protected
- Adaptation to the task of mandible meshing

Mesh morphing with „laplacian surface editing“



- Movement with
  - Master nodes (red)
  - Slave nodes (blue)

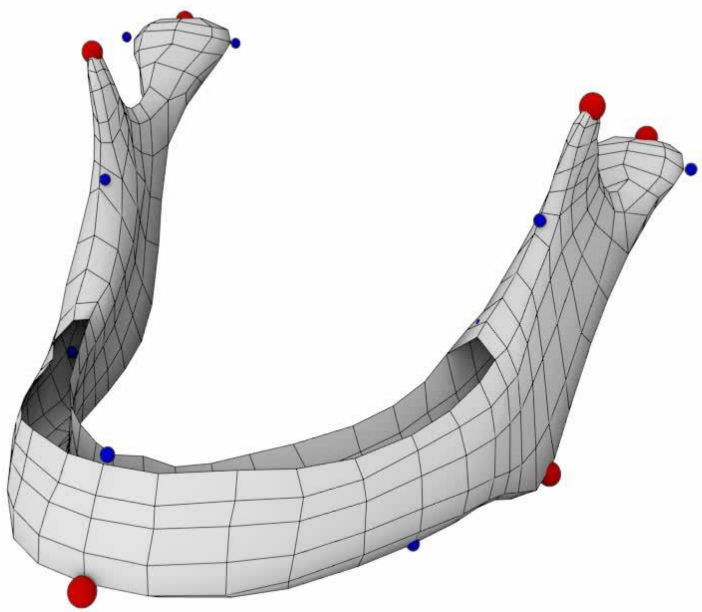
blender

- Acting on the coarse mesh

  (with 555 nodes)

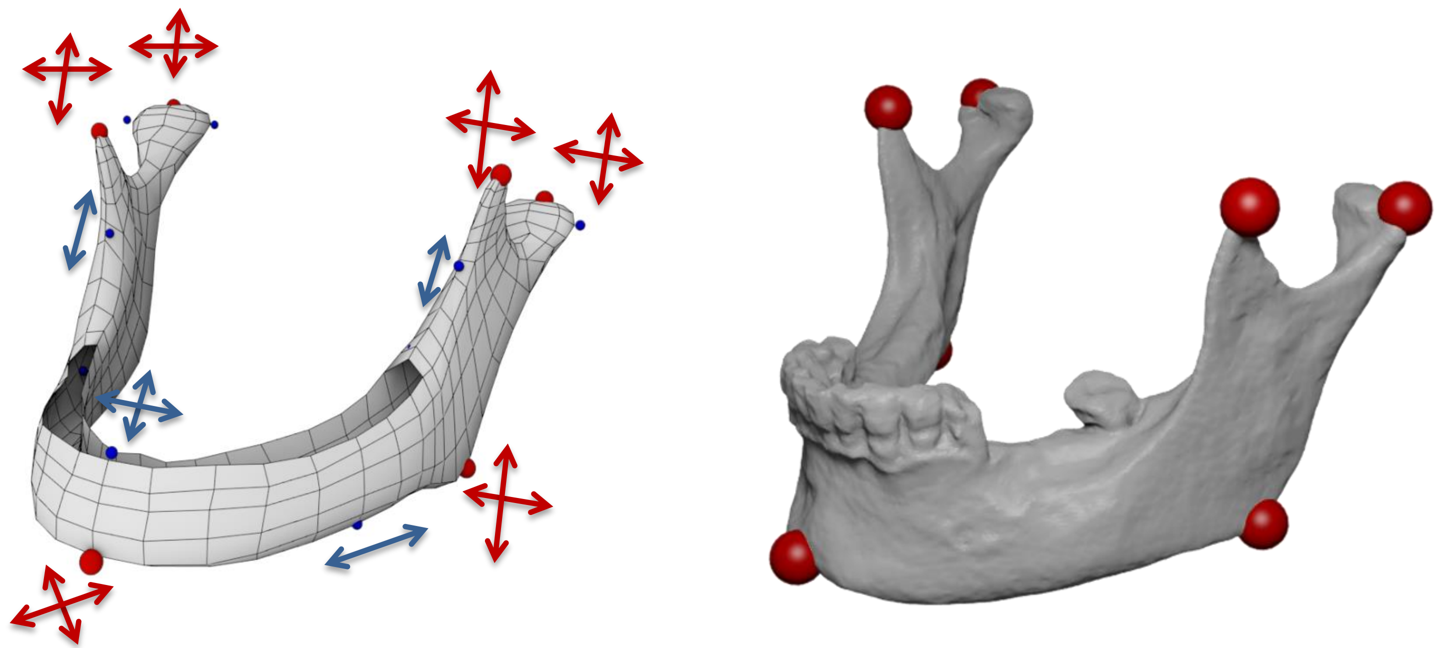
- Fast procedure
  - 2 to 3 minutes per mandible

Mesh morphing with „laplacian surface editing“



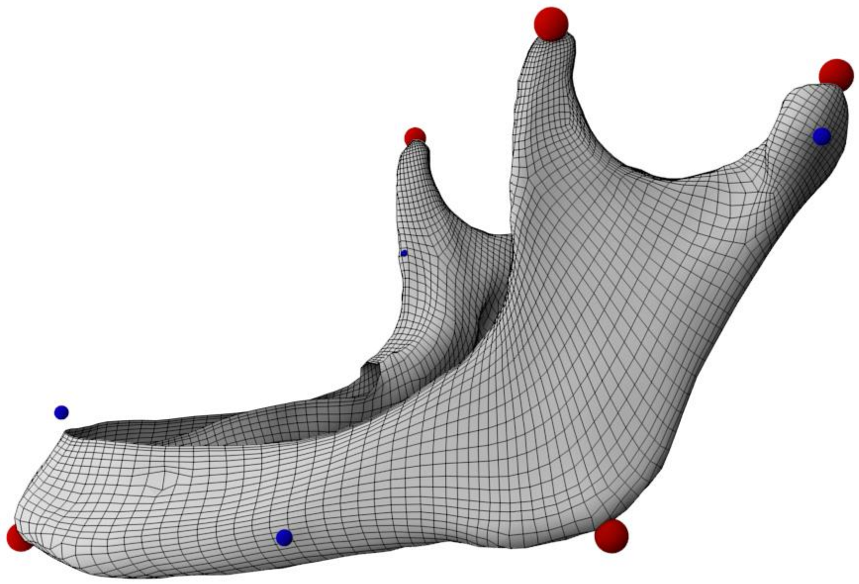
- Movement with
  - Master nodes (red)
  - Slave nodes (blue)
- Acting on the coarse mesh
  (with 555 nodes)
- Fast procedure
  - 2 to 3 minutes per mandible

Moving the landmark points to the matching individual positions



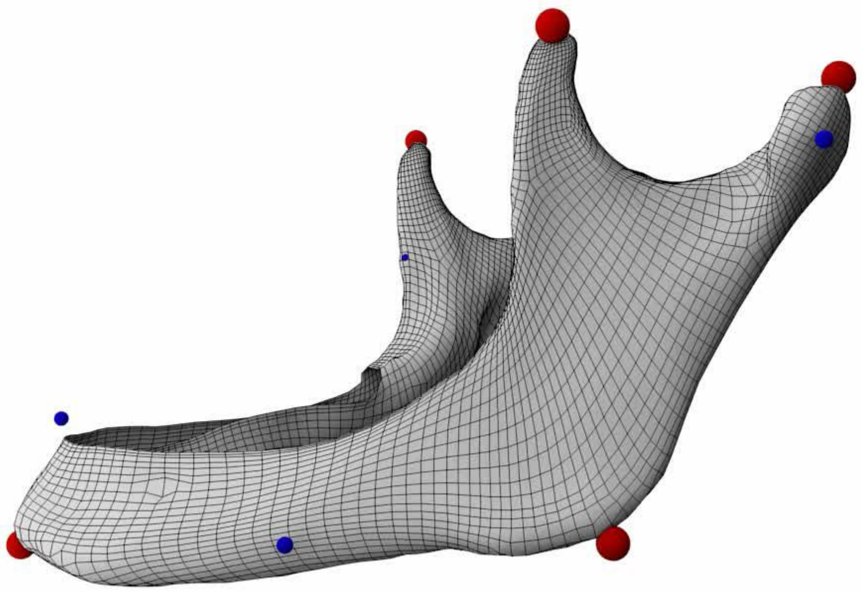
- Manual adjustement of standard master nodes to individual geometry
- First positioning of the master nodes
- and then fine tuning of the structure with slave nodes

Mesh projection



- Cascade of mesh modifications
  - Implemented with so called „shape modifiers“ in Blender
- Subsequent use of
  - Normal displacement
  - Shrink-wrap projection
  - Subdivision surface
  - Smoothing
  - Heuristic definition of optimal settings

Mesh projection



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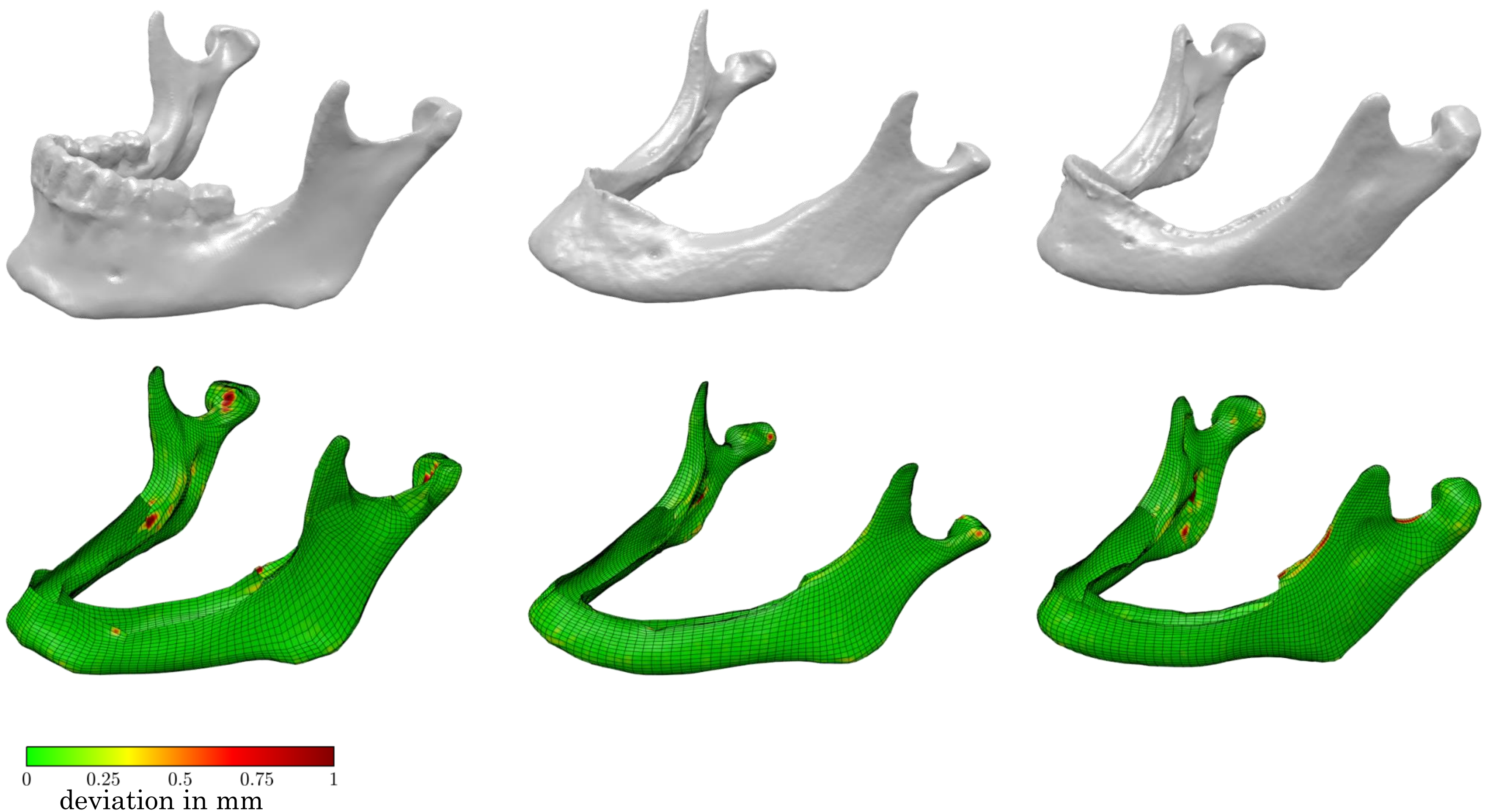
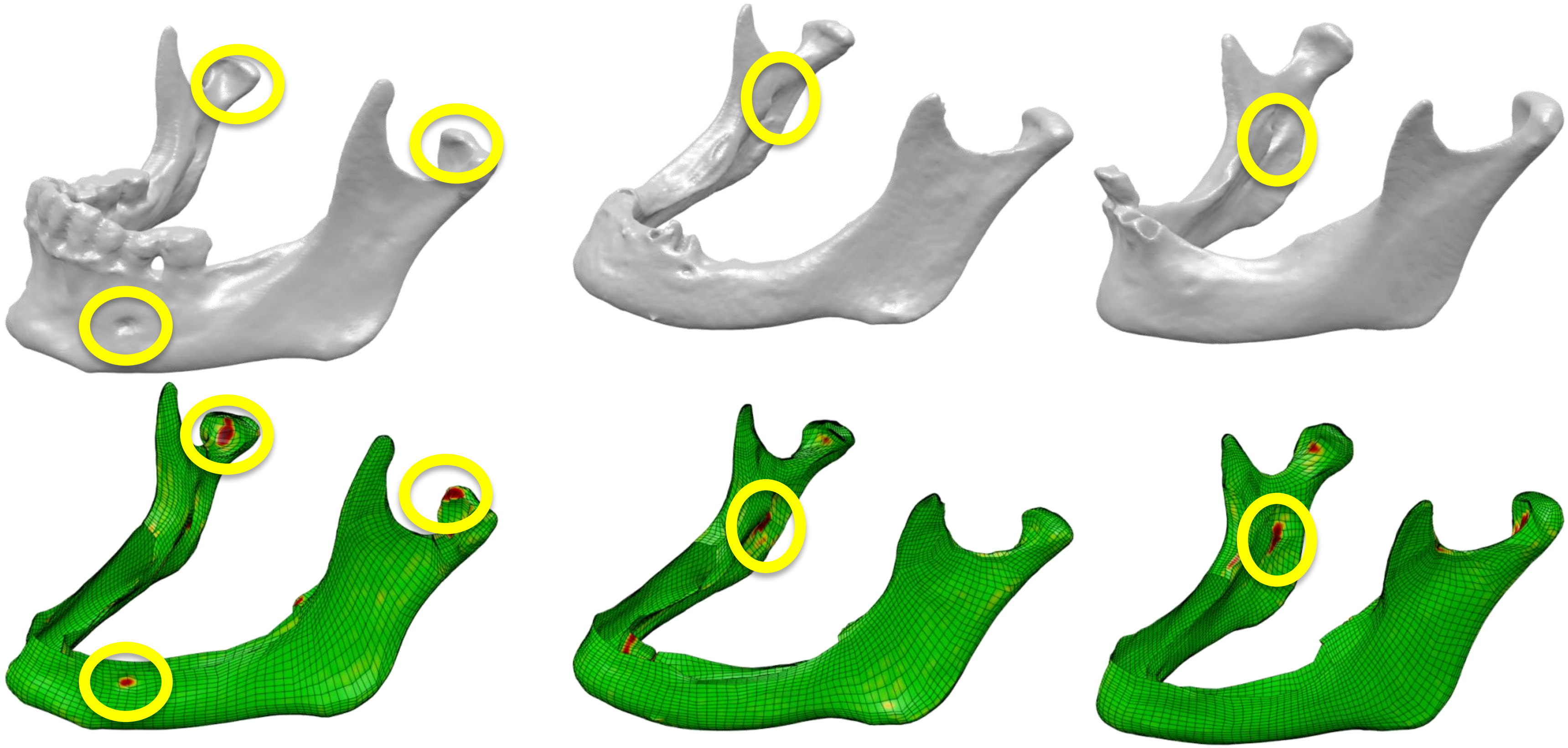
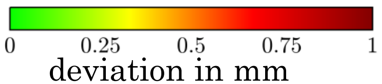
Comparison of segmented geometries and standardized representations



Comparison of segmented geometries and standardized representations





average deviation : 0.031 mm
maximal mean deviation: 0.042 mm

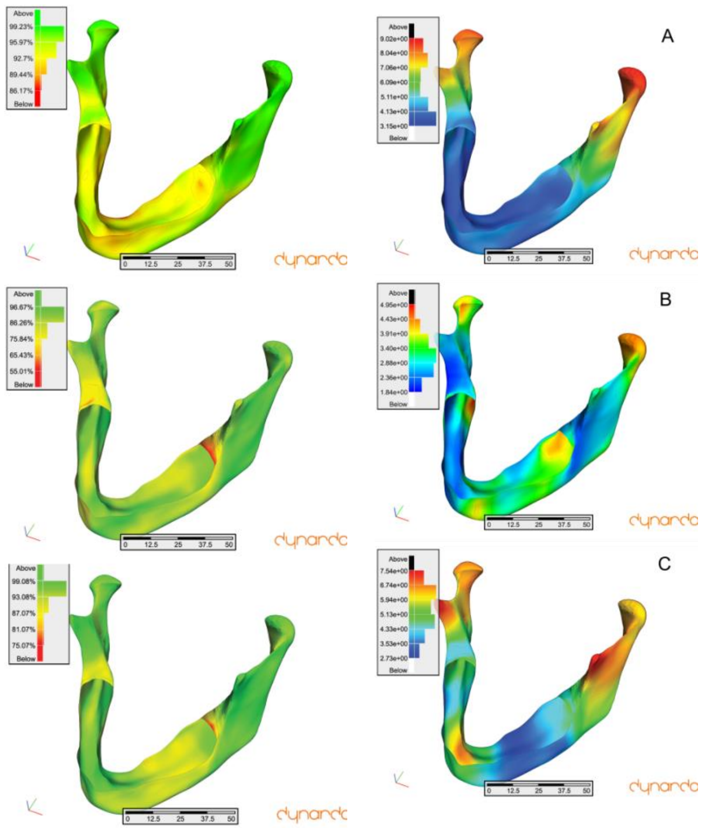
Optimal orientation of all mandible meshes: *Generalized Procrustes Analysis*

- J.C. Gower: Generalized procrustes analysis. Psychometrika 40: 33–51, 1975

- Optimal Adjustment of:
  - Translation
  - Rotation
- Both are set to a previously unknown common mean in an iterative procedure

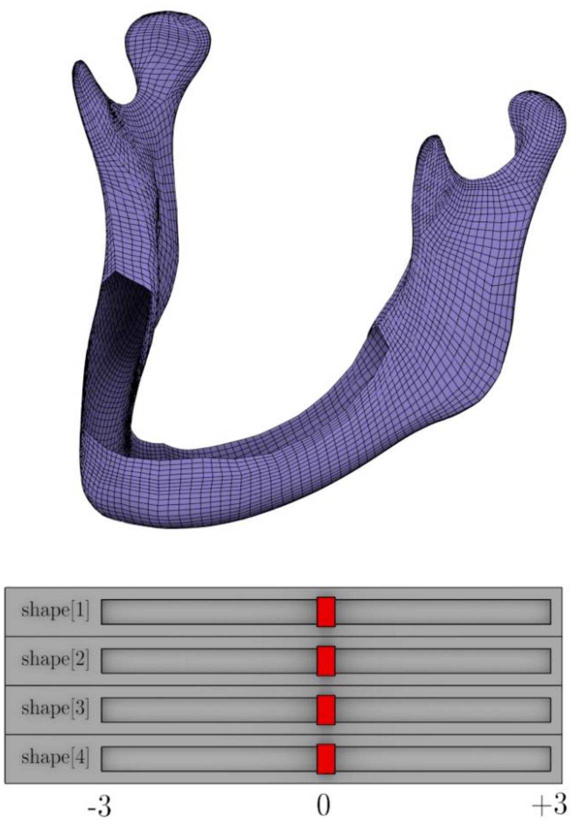
- B. Horn: Closed-form solution of absolute orientation using unit quaternions. J Otical Soc Am 4: 629–642, 1987

Statistical Analysis with
Statistics on Structures



- Karhunen-Loeve transformation
- scatter shapes
- local variations
- local accuracies, etc ….

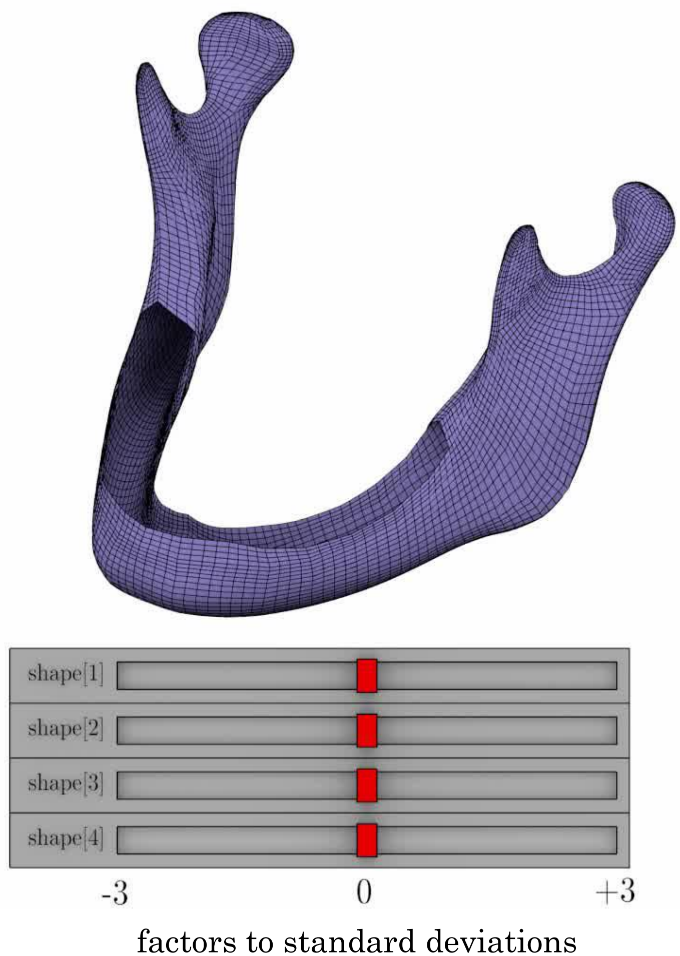
Interpretation of anthropometric variation as scattering input parameters



factors to standard deviation

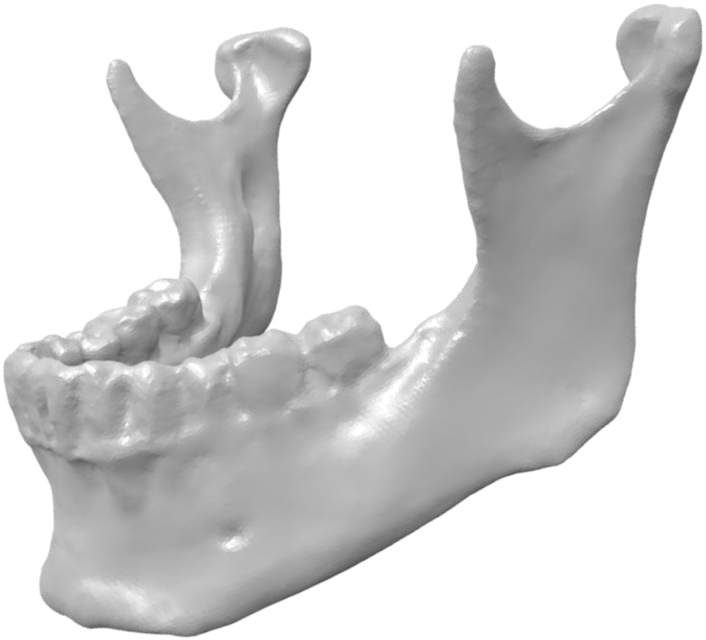
- In Blender a possibility for user interaction was implemented to provide direct access to all possible deformations (programed in *Python*)
- Standard deviations are shown for the purpose of orientation

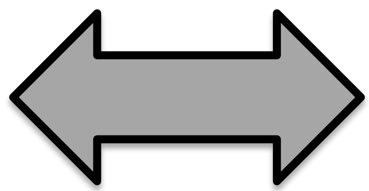
Visualization of scatter shapes

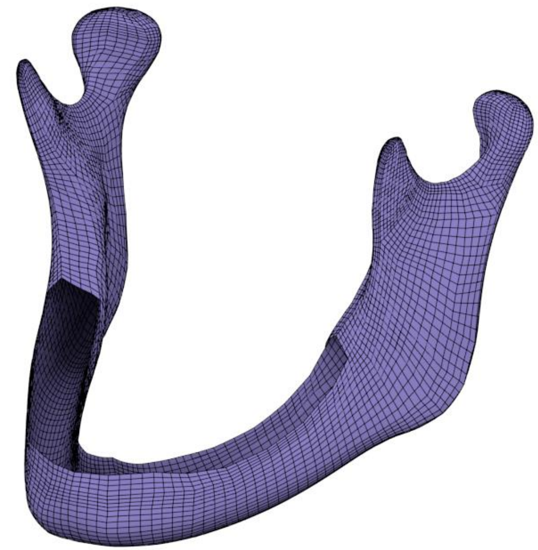


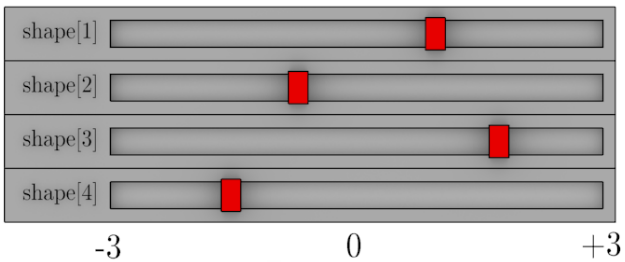
shape[1]	43.4607 %
shape[2]	54.4139 %
shape[3]	63.2348 %
shape[4]	68.7726 %
shape[5]	73.4525 %
shape[6]	77.0157 %
shape[7]	80.0189 %

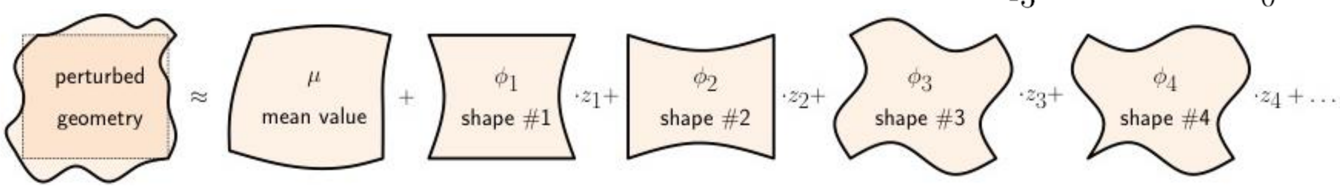
Amplitudes to match desired shapes





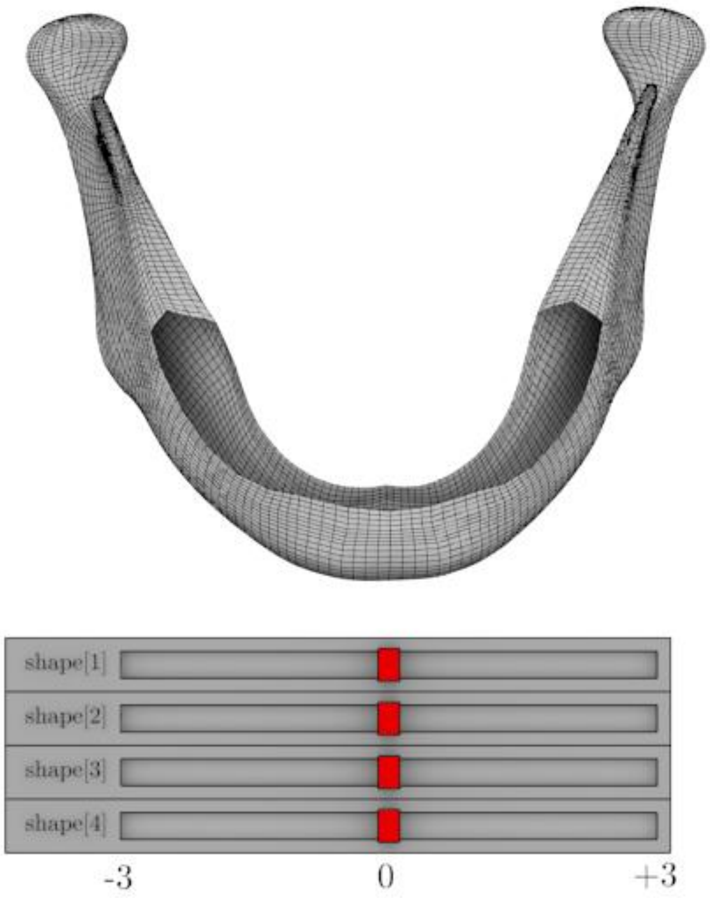




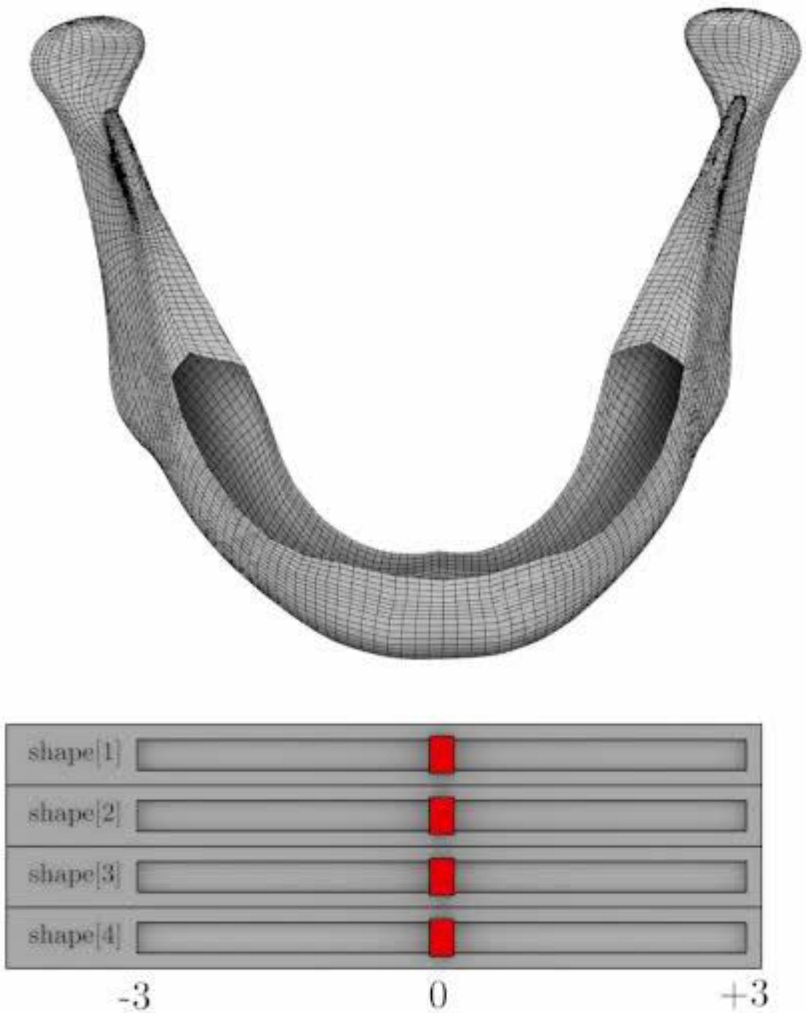


- Calculation of amplitudes that are suitable for best matches between standard geometry and actual mandible shapes

Visualization of amplitudes from **SoS**



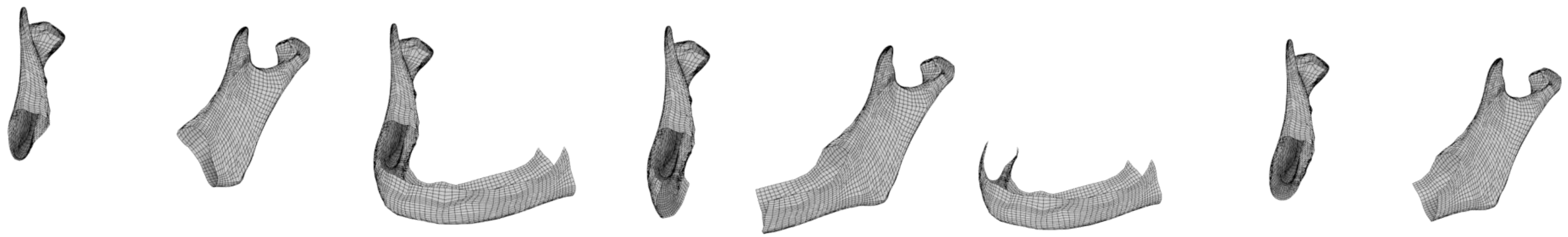
Visualization of amplitudes from **SoS**



Calculation of unknown shapes for surgical reconstructions

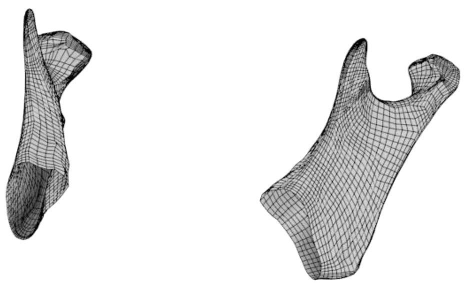
- Overview on experimental settings
  - whole collective of 63 mandibles
  - training set of 60 mandibles for statistical analysis
  - 3 mandibles that are not in that training set are chosen as target geometries for reconstructions

- 5 different example defects on each test mandible

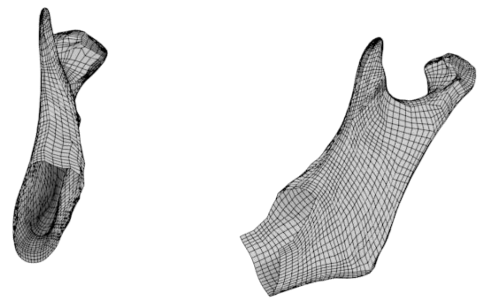


Reconstruction targets

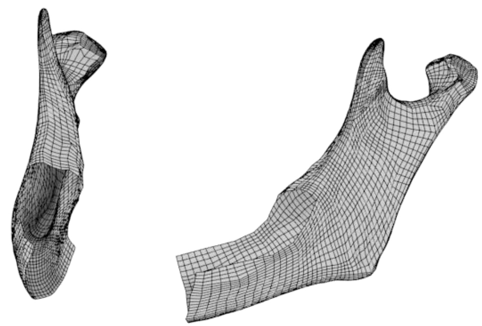
Corpus defect large



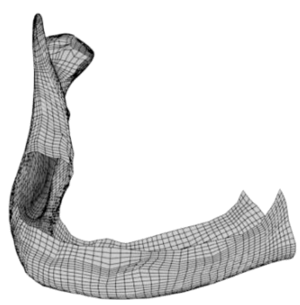
Corpus defect medium



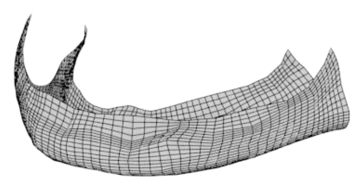
Corpus defect small



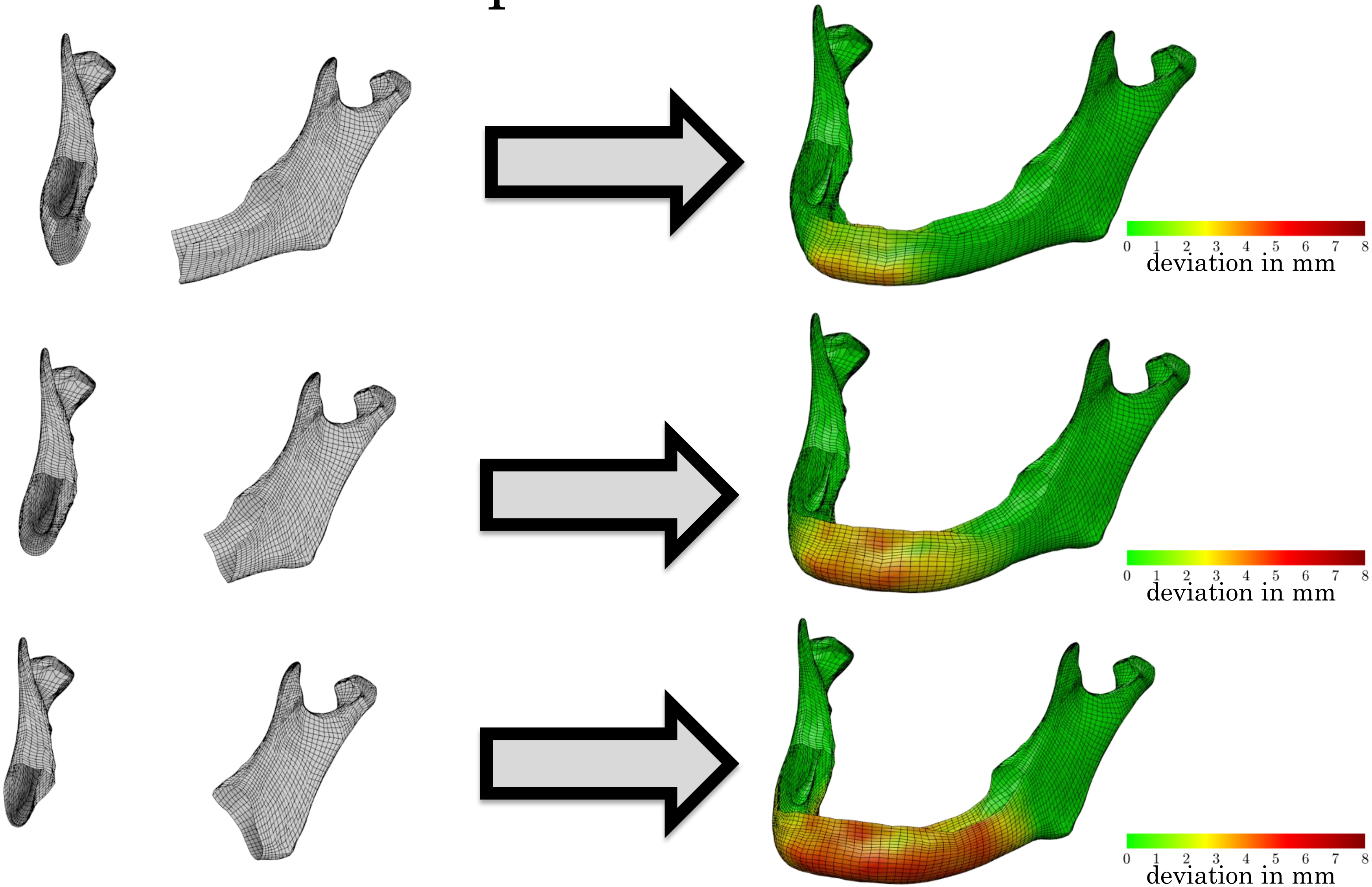
Ramus defect unilateral



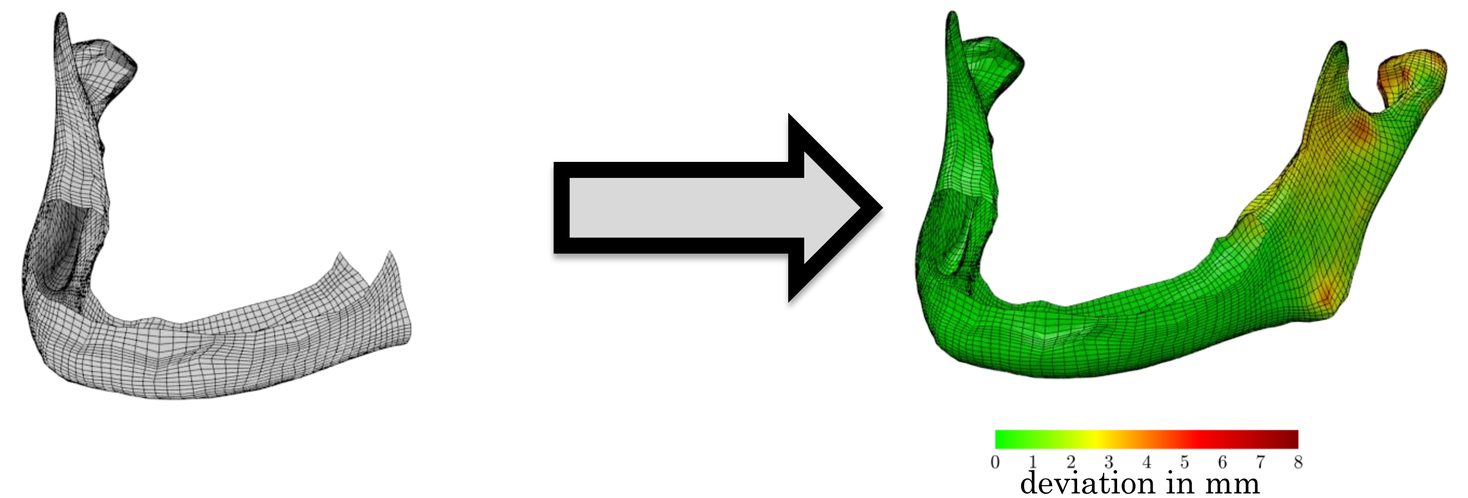
Ramus defect bilateral

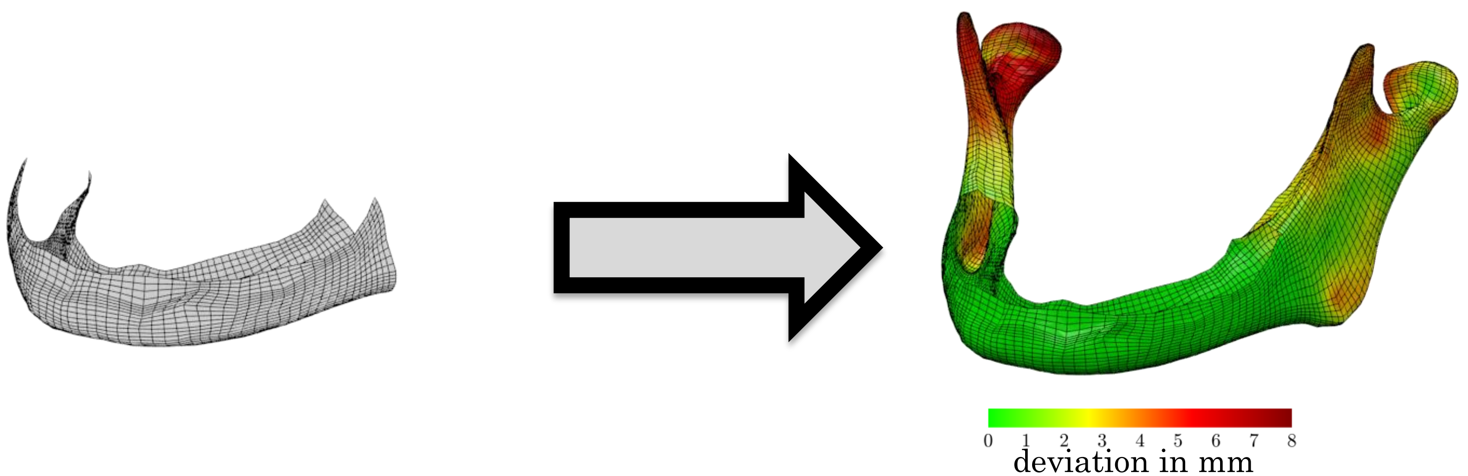


Example Reconstructions

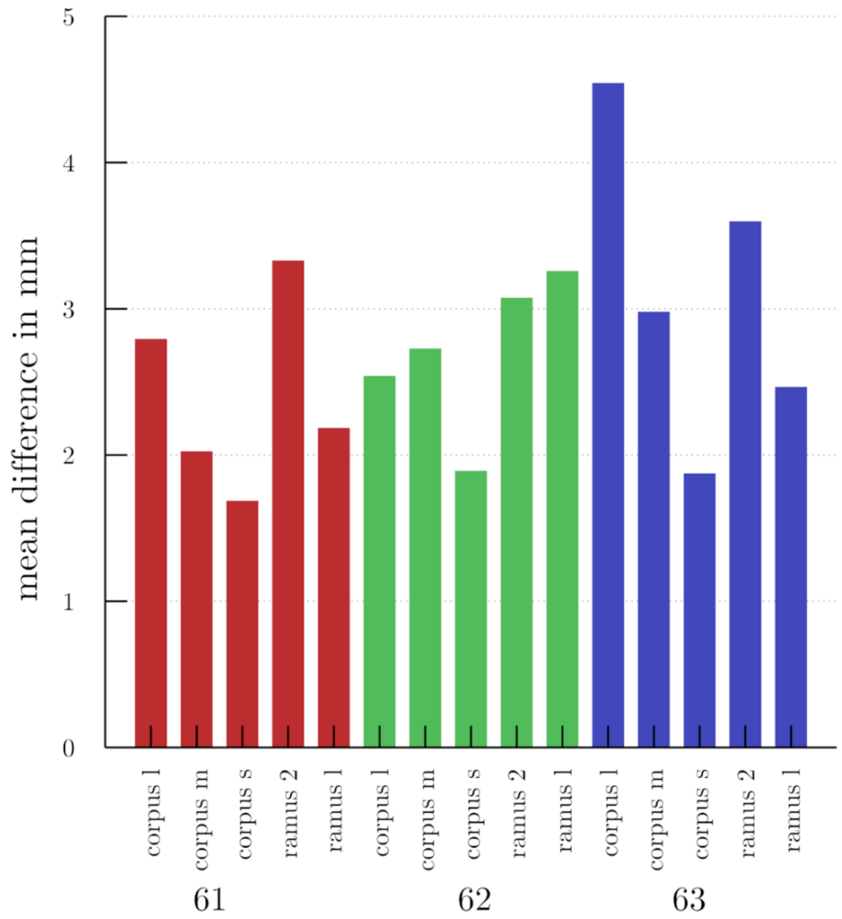


Example Reconstructions

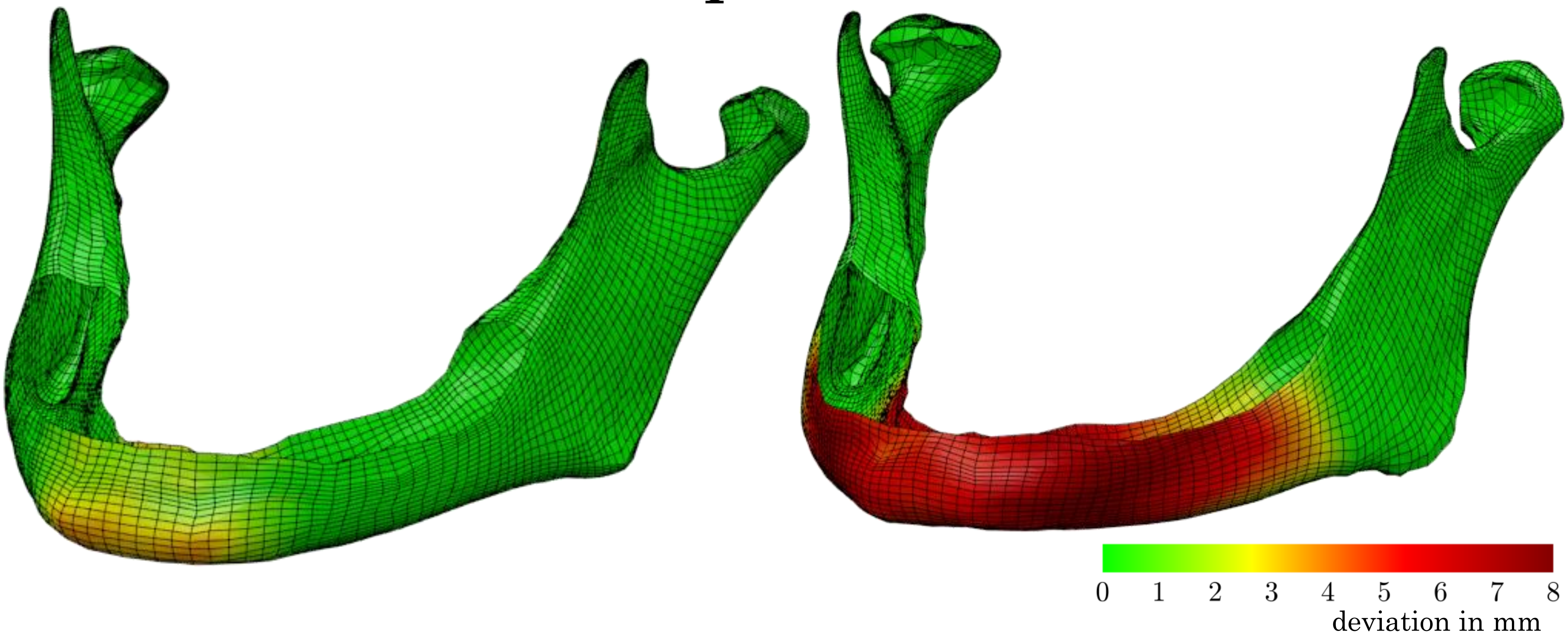




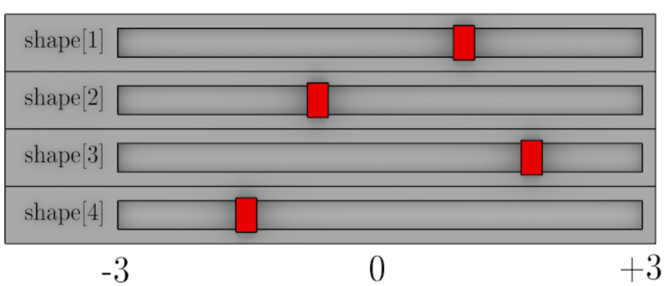
Comparison of reconstructions three different example mandibles



Good and Bad Examples for Reconstructions



- Accuracy correlates with defect size
- Upper jaw may be taken into account
- Further Manual adjustments are possible
  - -> statistically valid shapes

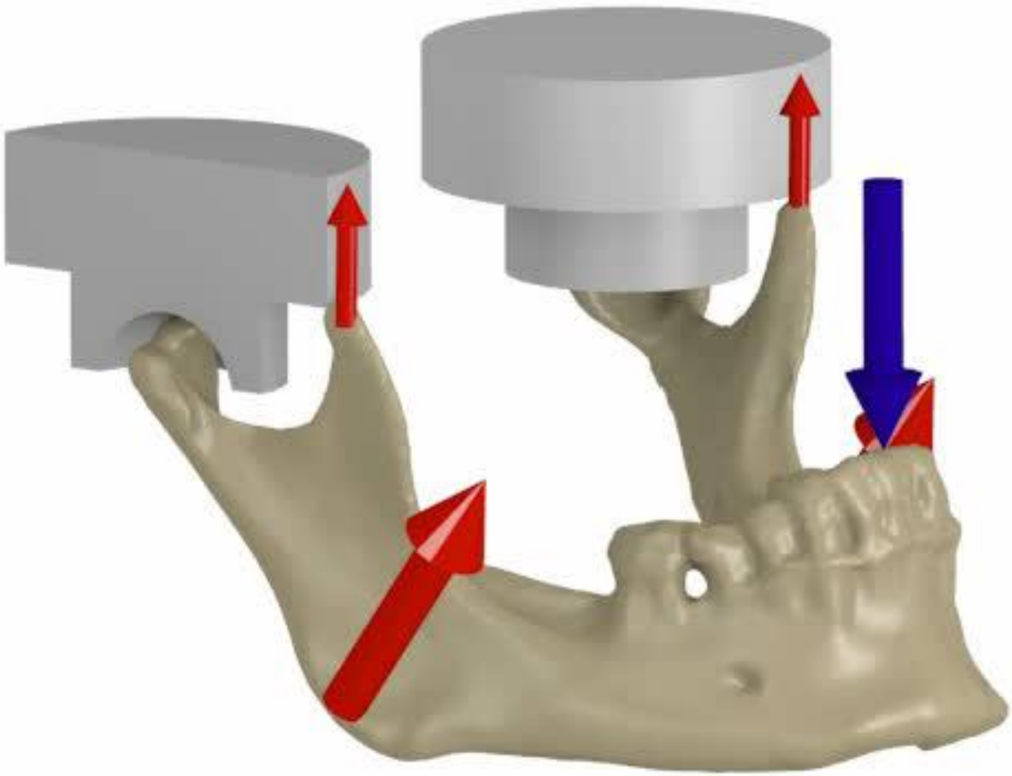


Conclusions and Outlook

- Workflow has shown to be applicable to the complex geometry of the human mandible
- Statistical shape analysis with SoS was feasible
- Reconstructions based on the given data are possible
  - Extensions of the data base may improve the method
- Variety of application of the newly available statistical data in biomechanics and bioengineering

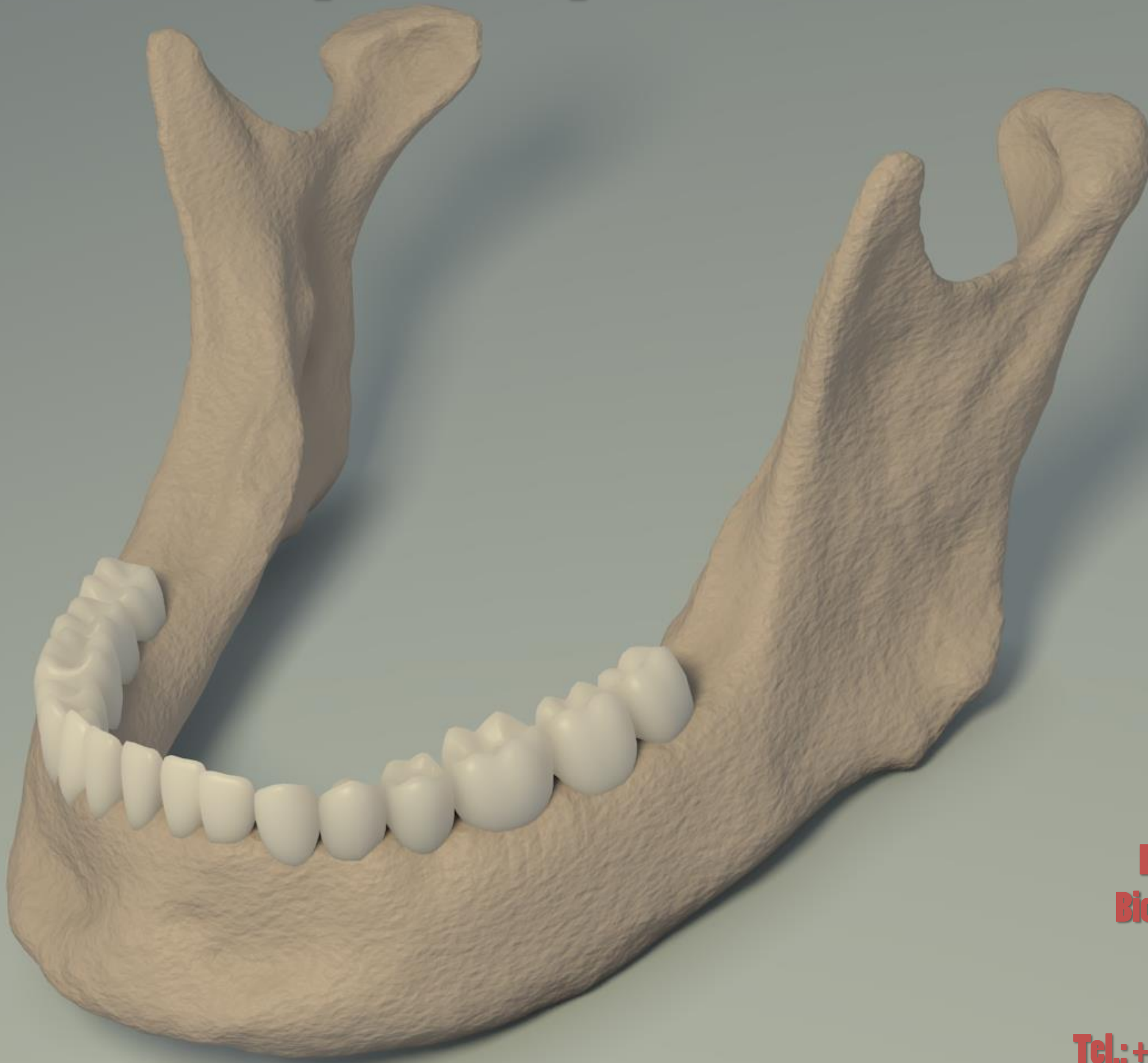
- Laplacian Surface Edition may in future be used for other (technical) application
  - Deformation of volumetric finite element meshes
    - Shape checking needs to be implemented (positive Jacobian)

Outlook: Mechanical Simulations in the presented process chain



Variation in bone geometry is essential for the biomechanical boundary conditions and the resulting stress distributions

Thank you for your attention



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