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Assessment of Peri-Articular Implant Fitting Based on Statistical Finite Element Modeling

S. Bonaretti[1], N. Reimers[2], M. Reyes[1], A. Nikitsin[1], A. Joensson[2], L.-P. Nolte[1], P. Büchler[1]

[1] ARTORG Center for Biomedical Engineering Research, University of Bern, Bern, Switzerland
[2] Stryker Osteosynthesis, Kiel, Germany

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CO-ME
COMPUTER AIDED AND IMAGE GUIDED MEDICAL INTERVENTIONS

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How to make an implant “fit” a majority of people?

How to make an implant “fit” a majority of people?

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- Current implant design is based on limited knowledge about the target anatomy
- Existing possibilities:
  - Anthropomorphic data from the literature (incomplete information)
  - Cadaver experiments (fail to capture variability across individuals)
- There is no good model about the range of variability of bone shape (and bone quality) in a given target population

Our Proposal: An Overview

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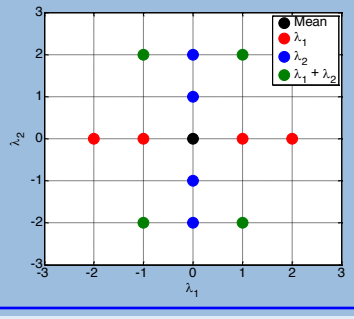
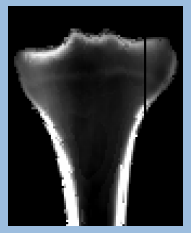
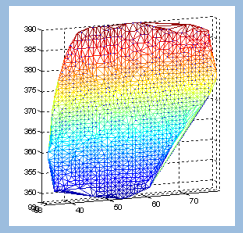
Statistical Shape Models

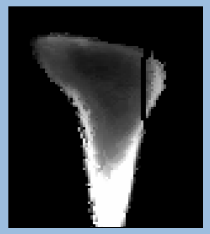
Principal Component Analysis



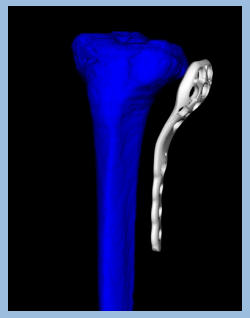
Fracture Creation

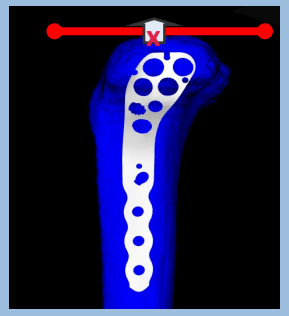




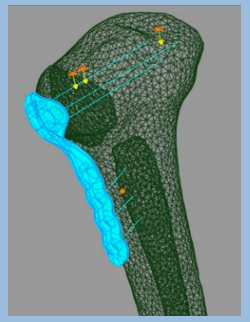


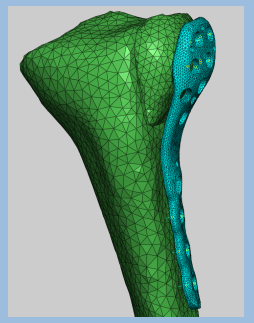
Bone-Implant Fitting





Finite Element Analysis





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Statistical Shape Model

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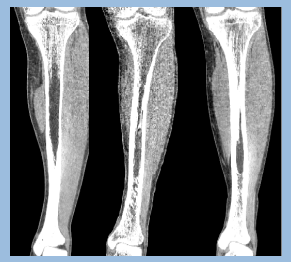
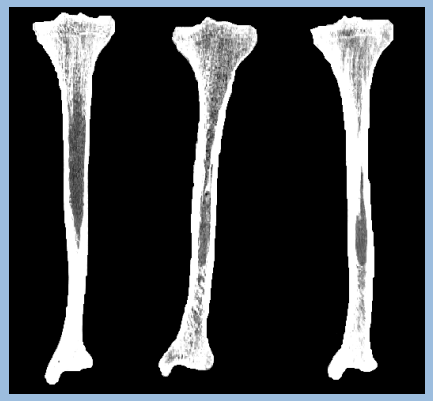
> CT collection of different population:

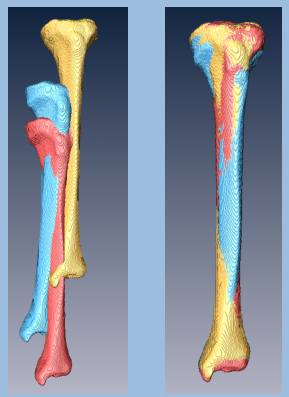
43 Caucasian left tibias: 23 males, 20 females
47 Asian left tibias: 28 males, 19 females



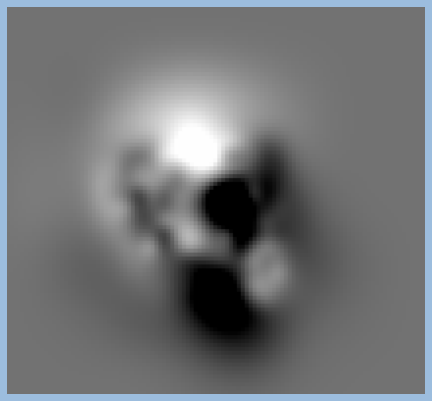
> Image pre-processing:



Segmentation



Rigid registration

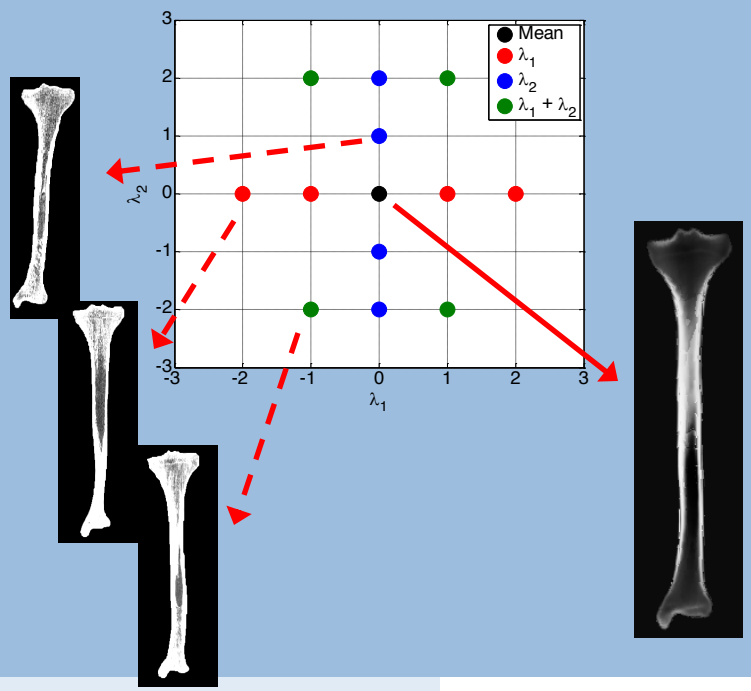


Non-Rigid registration

Statistical Shape Model

- Landmark selection: Voxel based approach
- Principal Component Analysis: new instances for each population

$$x = \bar{x} + \phi_1 b_1 + \phi_2 b_2, \quad |b_i| \leq \pm 3\sqrt{\lambda_i}$$



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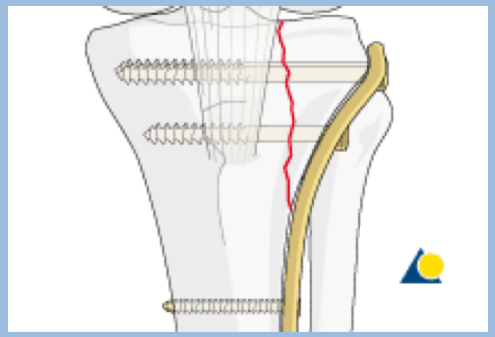
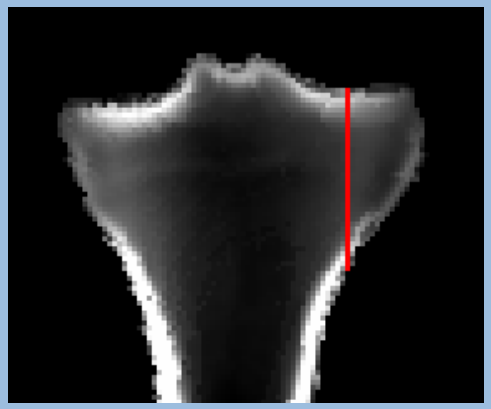
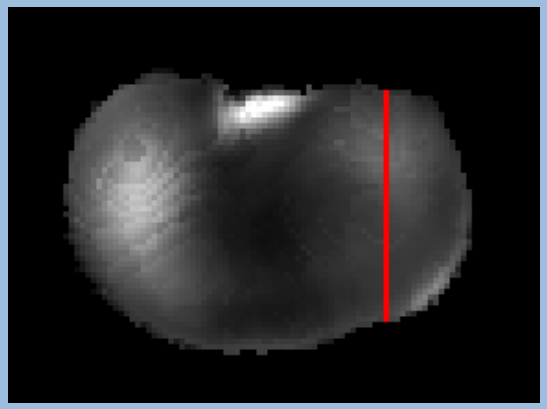
Fracture Creation

- Chosen fracture: 41-B1



- Fracture creation (mean bone):





Fracture Propagation

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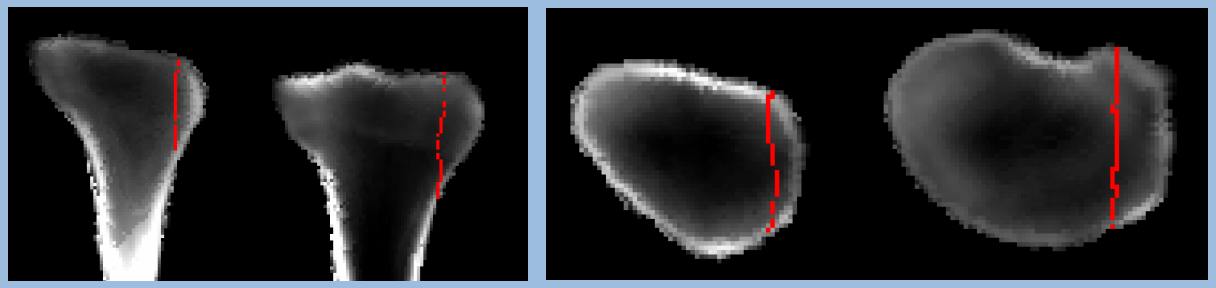
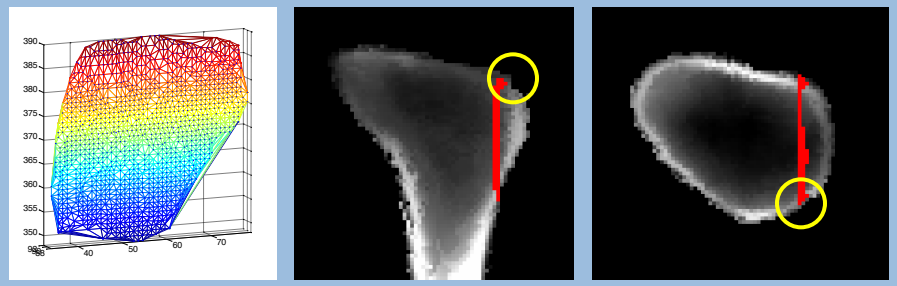
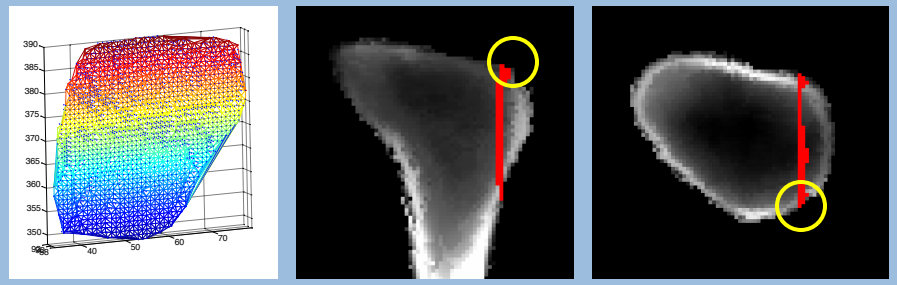
- Propagation using deformation fields:



- Surface creation using a mesh:



- Edge voxel deletion (mesh expansion):



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Bone-Implant Fitting

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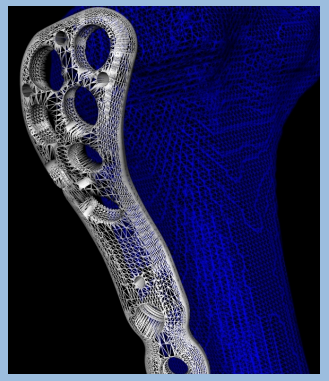
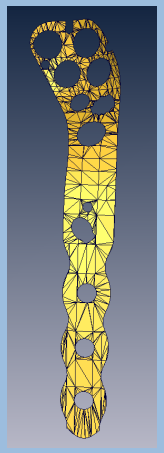
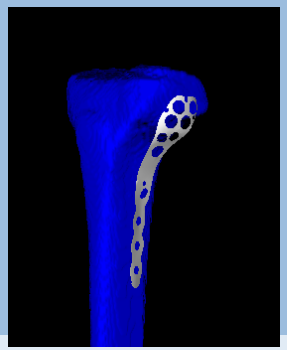
- Both bone and implant represented like meshes:



- Implant inner surface extraction:

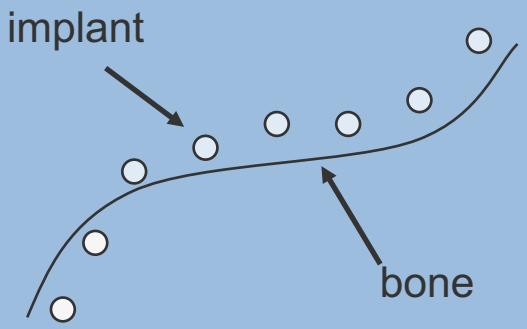


- Manual initialization:

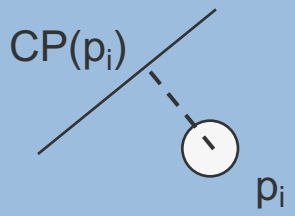


Bone-Implant Fitting

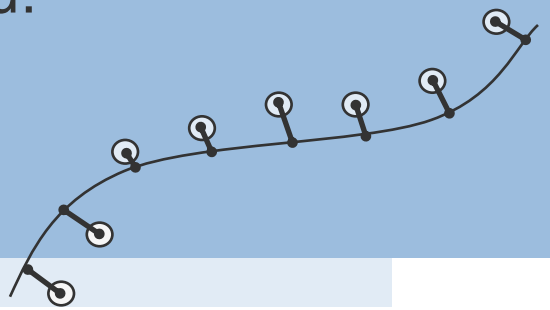
> Iterative Closest Point Algorithm: $\boxed{\arg\min \sum \|e_i\|}$



$$\|e_i\| = \text{dist}(p_i, CP(p_i))$$

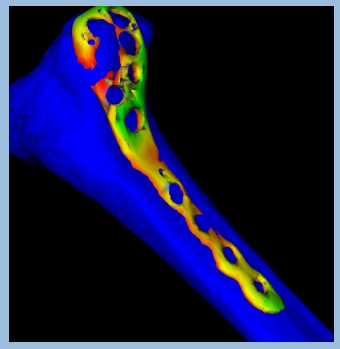


> Closest points are iteratively found on the target shape and a new rigid transformation is computed:

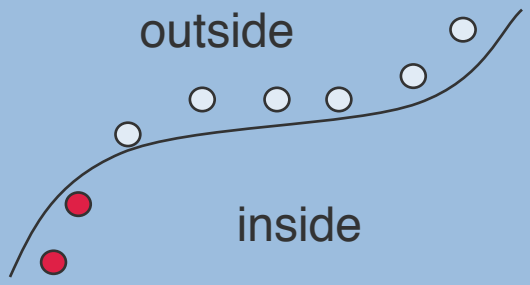


Bone-Implant Fitting – Local Constraints

> Collision constraint:



> Constrained Iterative Closest Point: $\boxed{\operatorname{argmin} \sum w_i \|e_i\|}$



$$w_i \begin{cases} 1.0 & \text{if outside} \\ K_i \|e_i\| & \text{if inside} \end{cases}, \quad \underset{\forall i \in V_{inside}}{K_i} > \frac{(N_{total} - N_{inside})}{\sum_{i \in V_{inside}} \|e_i\|}$$

Bone-Implant Fitting – Global constraints

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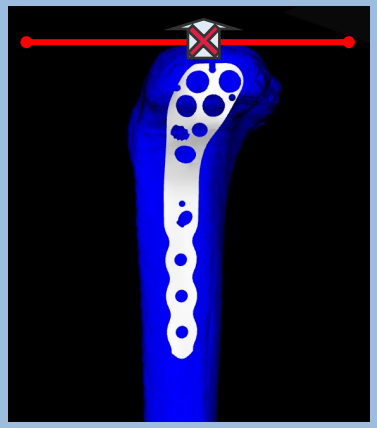
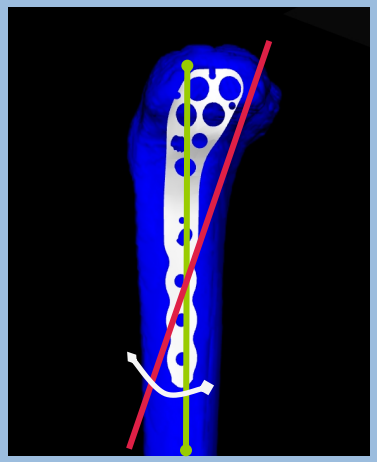
- Plateau constraint:



$$\forall p(x,y,z) \in \text{implant}$$

$$z < Z_{plateau}$$

- Parallelism constraint:



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Finite Element Analysis

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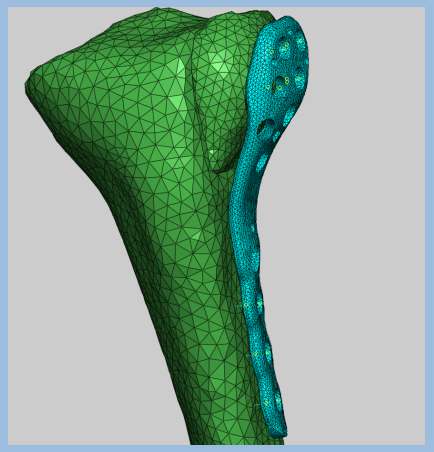
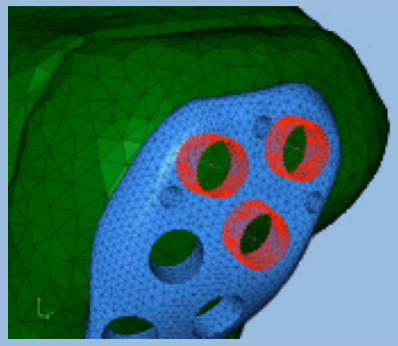
- Bone and implant are meshed with 10-node tetrahedrons



- Screws modeled with beam elements
  - Circular section (radius 3.3mm)
  - Connection to the bone made with embedded elements



Finite Element Analysis

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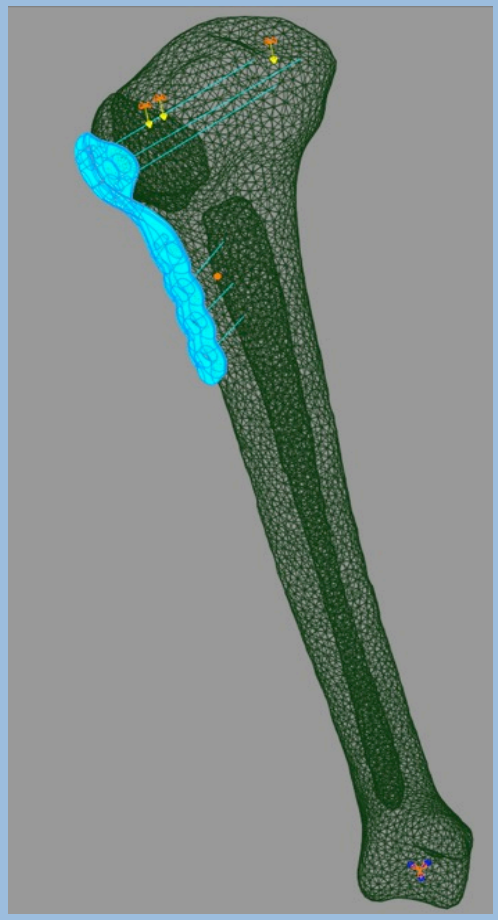
- Mechanical properties:
  - Bone: $E=6.95\rho^{1.49}$
  - Implant: titanium properties

    (E = 110 000 MPa; Poisson's ratio = 0.3)

- Boundary conditions:
  - 2 times body weight
  - Distal extremity fixed
  - Bone/bone contacts



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Results: Asian/Caucasian distance maps

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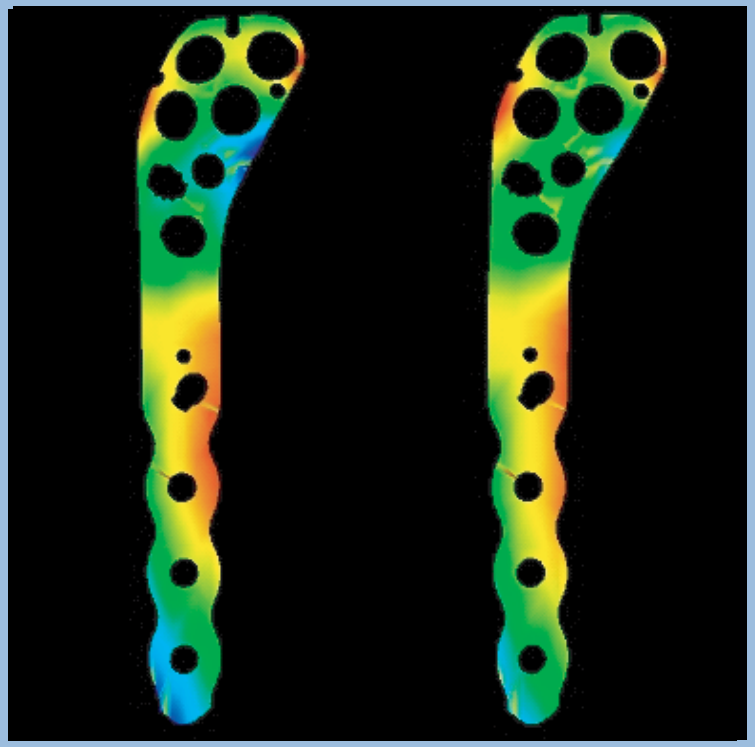
Average distance

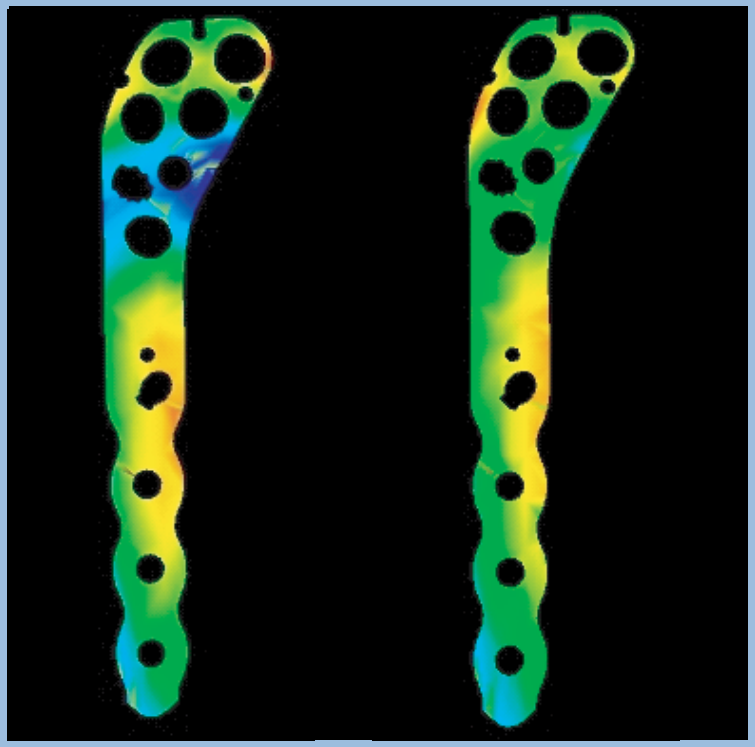
Asian Caucasian



Range: 0 – 4 mm

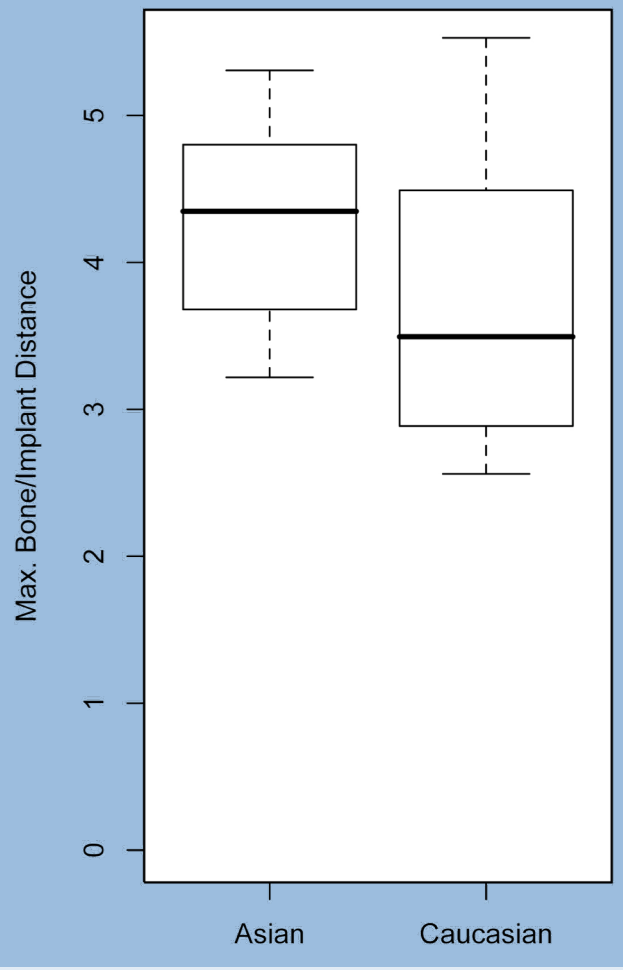
Max. distance

Asian Caucasian



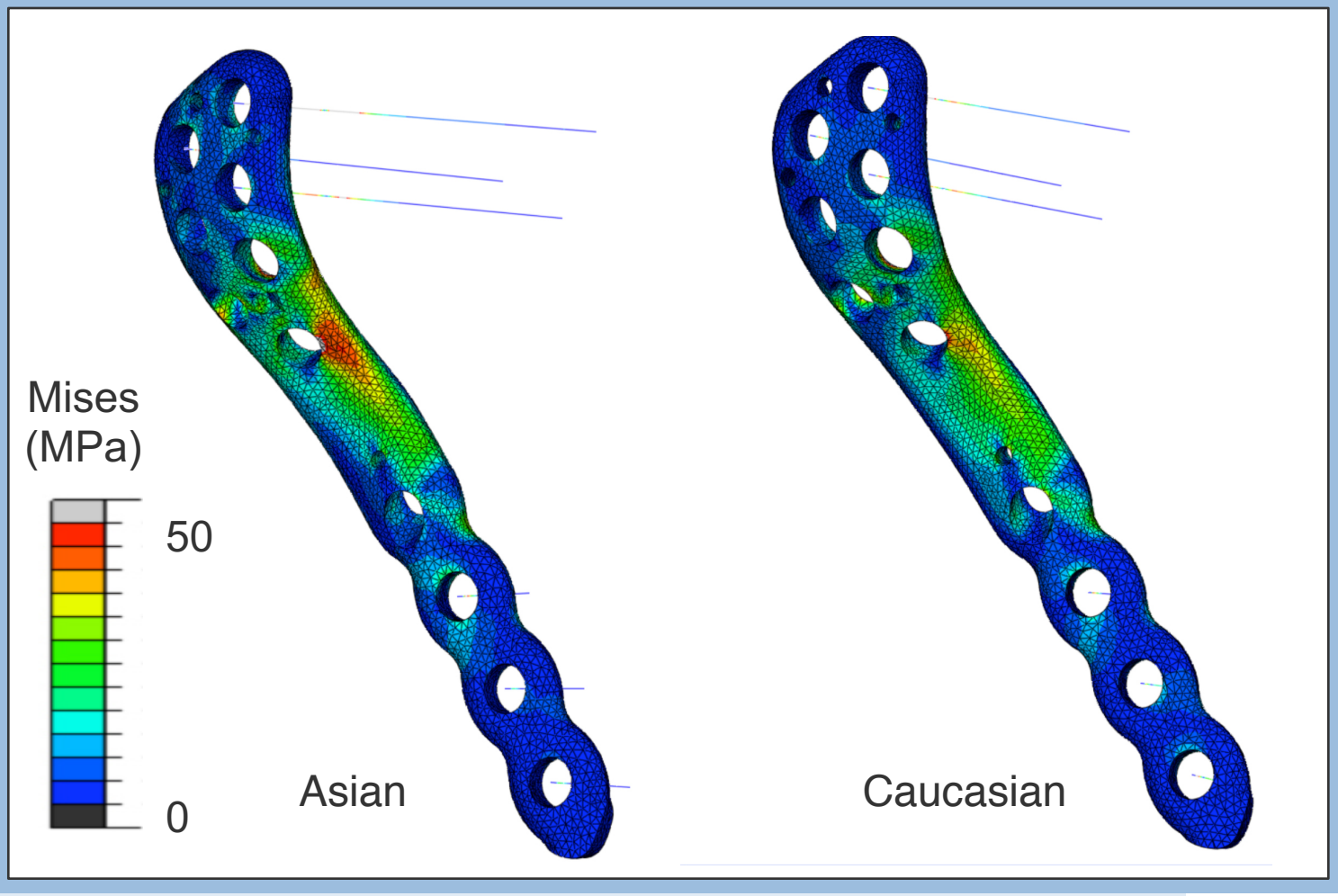
Range: 0 – 7 mm

Results: Asian/Caucasian distance maps



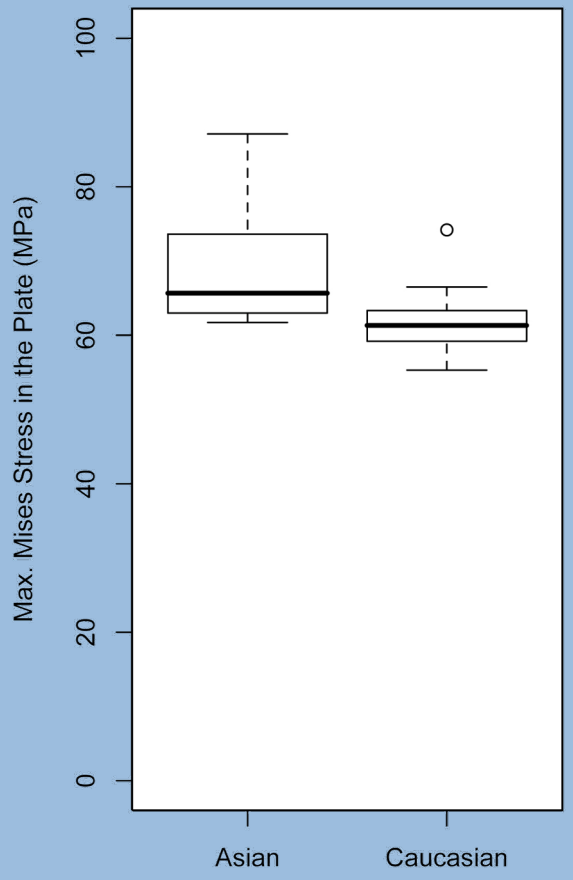
> No statistical differences between Asian and Caucasian

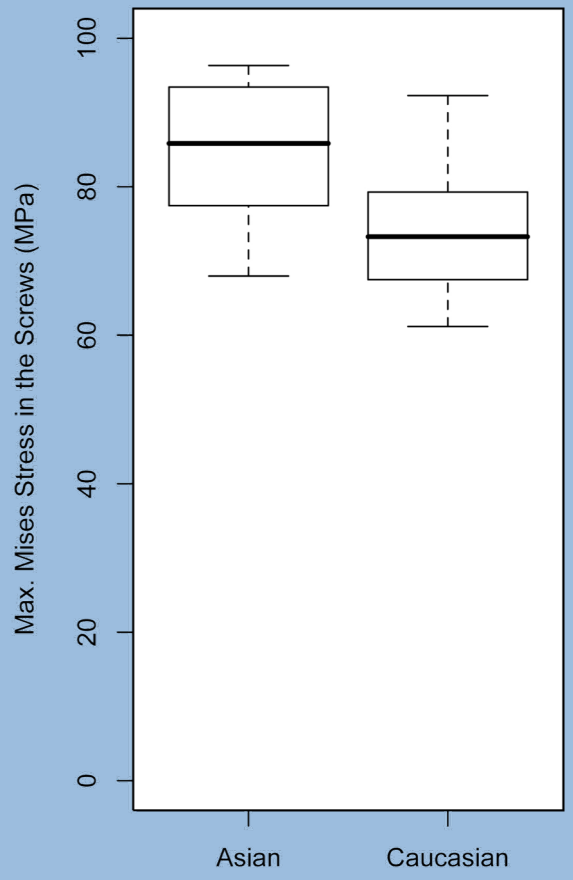
Results: Stress in the plate



Results: Stress in the plate

- Stresses below Yield stress
- Higher stresses for Asian than for Caucasian ($p < 0.05$)





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Discussion

- Assessment of orthopaedic implant fitting combining Statistical Shape Models and Finite Element Analysis
- Non-rigid-registration-based procedure:
  - No landmark definition
  - Method for fracture propagation
- The biomechanical analysis highlights details that the shape fitting can not detect (statistical significance)

Future work

- Simulation of reality:
  - Adding populations (Africans, …)
  - Adding statistical modeled intensity to the bones
  - Different kind of fractures
  - Screw positions
  - Loading and boundary conditions

Acknowledgements

- All co-authors
  - Mauricio Reyes: Bone-Implant Fitting
  - Andrei Nikitsin: Finite Element Analysis
  - Philippe Büchler: Supervision
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Thank you!