

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

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 - Statistical Shape Model
 - Fracture Creation and Propagation
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How to make an implant “fit” a majority of people?

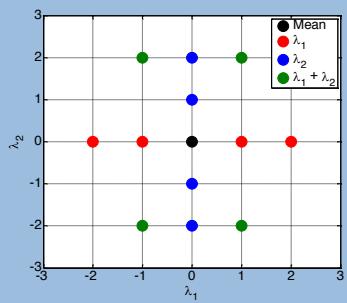
- > Current implant design is based on limited knowledge about the target anatomy
- > Existing possibilities:
 - Anthropomorphic data from the literature (incomplete information)
 - Cadaver experiments (fail to capture variability across individuals)
- > There is no good model about the range of variability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

Our Proposal: An Overview

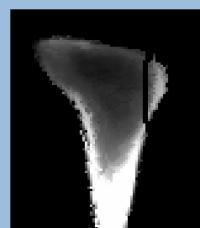
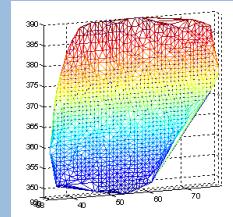
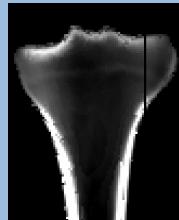
Statistical Shape Models



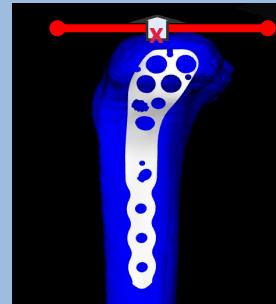
Principal Component Analysis



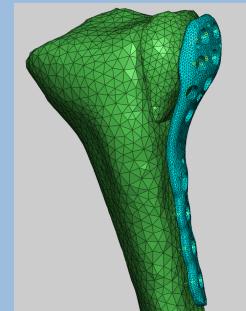
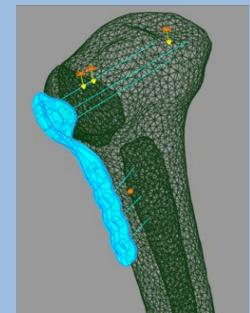
Fracture Creation



Bone-Implant Fitting



Finite Element Analysis



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Statistical Shape Model

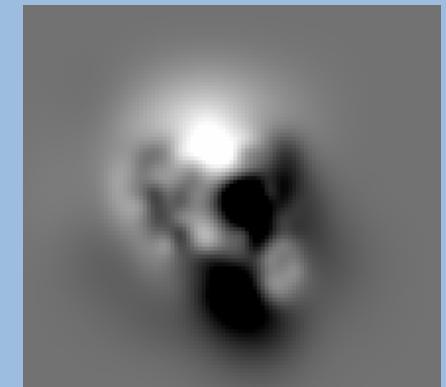
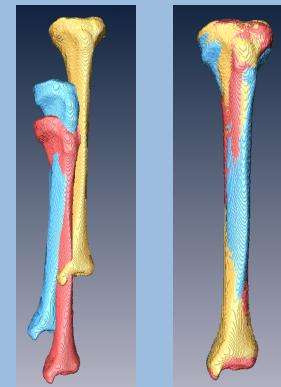
- > CT collection of different population:

43 Caucasian left tibias: 23 males, 20 females

47 Asian left tibias: 28 males, 19 females



- > Image pre-processing:



Segmentation

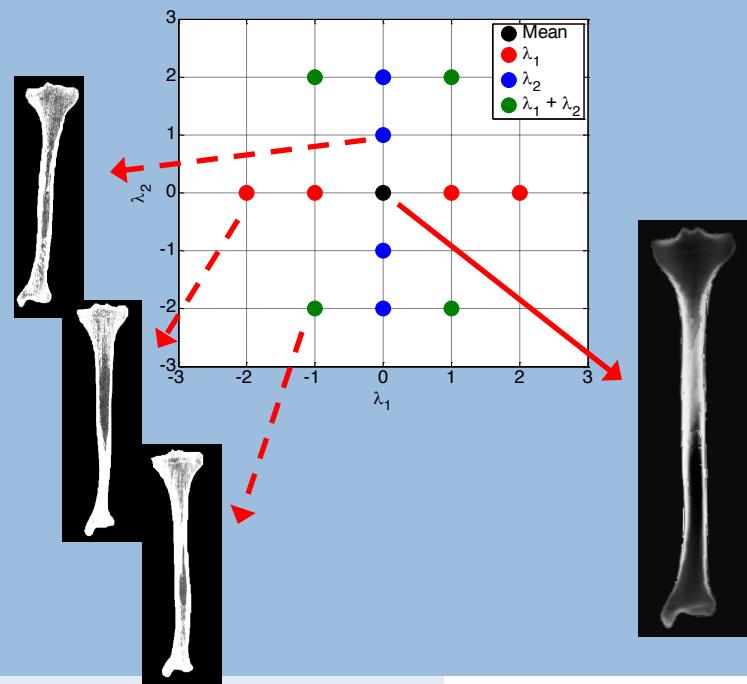
Rigid registration

Non-Rigid registration

Statistical Shape Model

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

$$\mathbf{x} = \bar{\mathbf{x}} + \phi_1 \mathbf{b}_1 + \phi_2 \mathbf{b}_2, \quad |\mathbf{b}_i| \leq \pm 3\sqrt{\lambda_i}$$

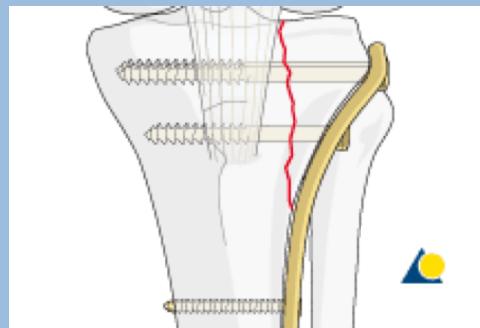


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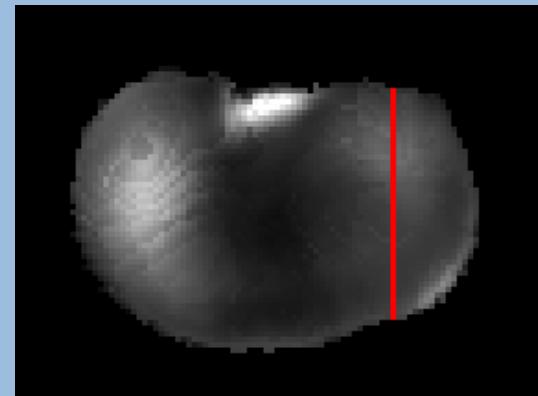
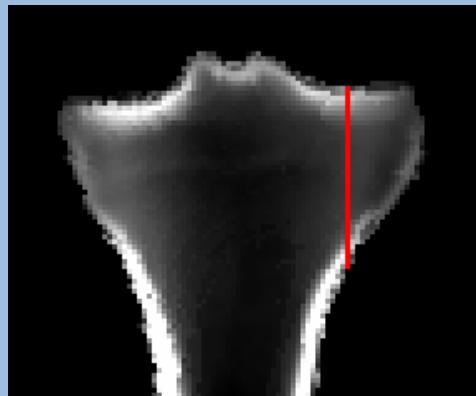
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Fracture Creation

- > Chosen fracture: 41-B1

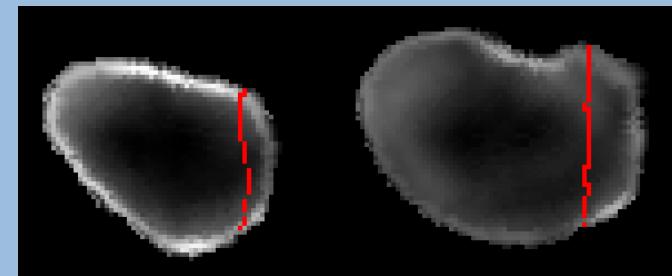
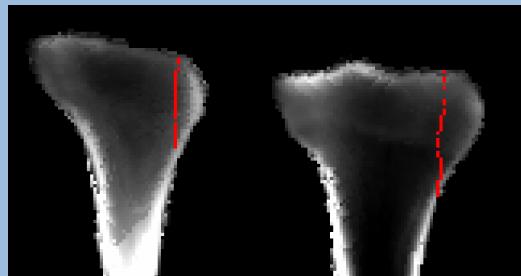


- > Fracture creation (mean bone):

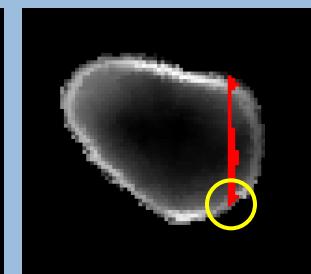
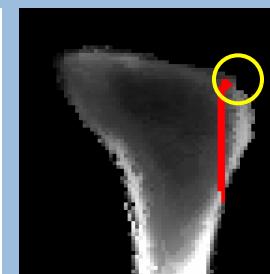
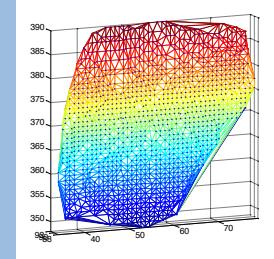


Fracture Propagation

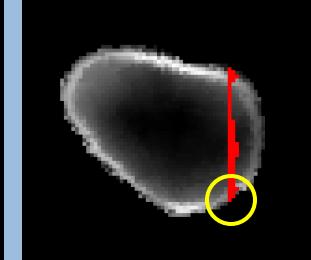
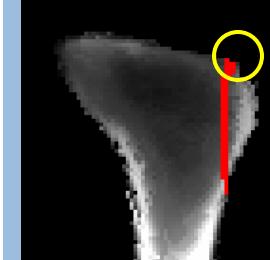
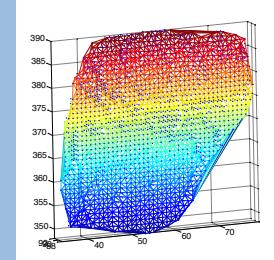
- > Propagation using deformation fields:



- > Surface creation using a mesh:



- > Edge voxel deletion (mesh expansion):

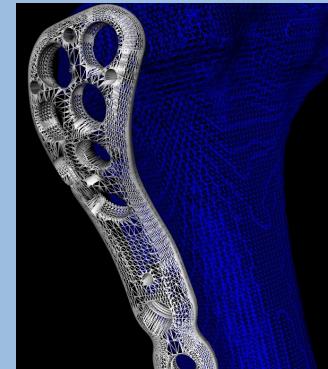
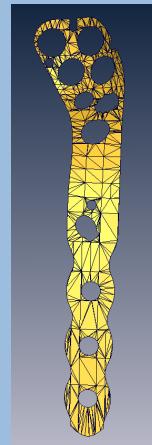
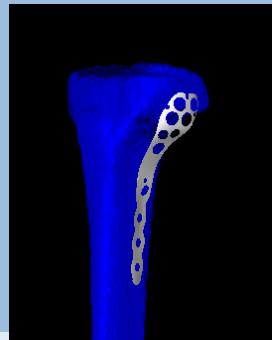


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Bone-Implant Fitting

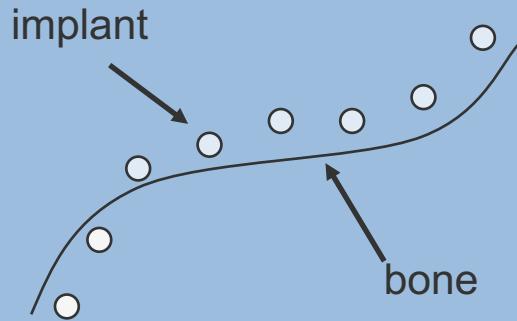
- > Both bone and implant represented like meshes:
- > Implant inner surface extraction:
- > Manual initialization:



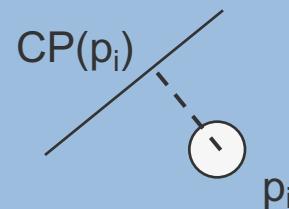
Bone-Implant Fitting

- > Iterative Closest Point Algorithm:

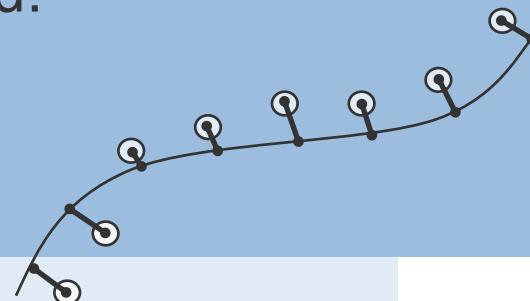
$$\operatorname{argmin} \sum \|e_i\|$$



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

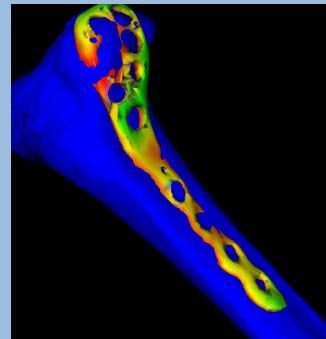


- > Closest points are iteratively found on the target shape and a new rigid transformation is computed:

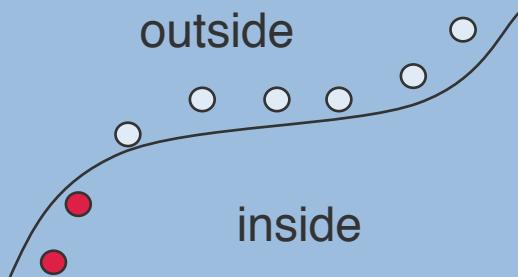


Bone-Implant Fitting – Local Constraints

- > Collision constraint:



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

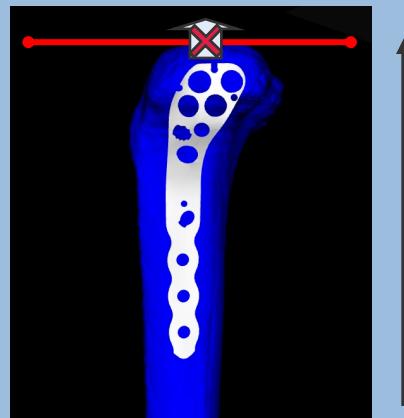


$$w_i \begin{cases} 1.0 & \text{if outside} \\ K_i \|e_i\| & \text{if inside} \end{cases}$$

$\forall i \in V_{\text{inside}}, \frac{K_i}{\sum_{i \in V_{\text{inside}}} K_i} > \frac{(N_{\text{total}} - N_{\text{inside}})}{\sum \|e_i\|}$

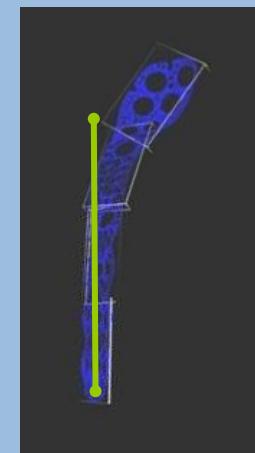
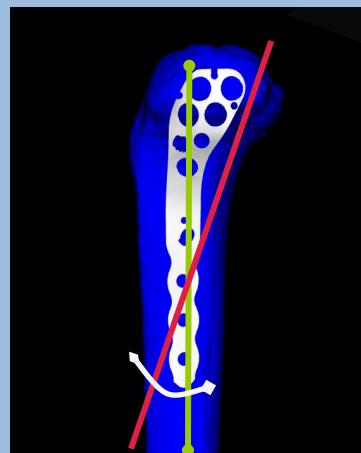
Bone-Implant Fitting – Global constraints

- > Plateau constraint:



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

- > Parallelism constraint:

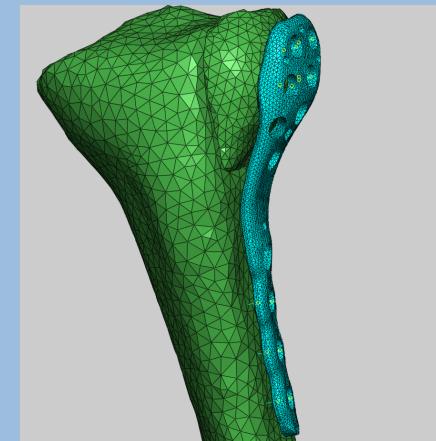


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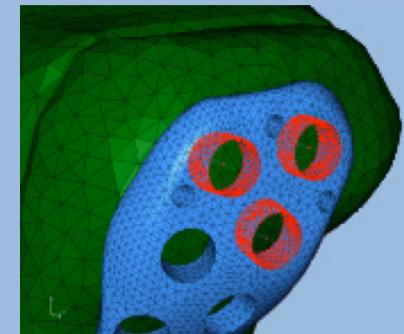
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Finite Element Analysis

- > Bone and implant are meshed with 10-node tetrahedrons



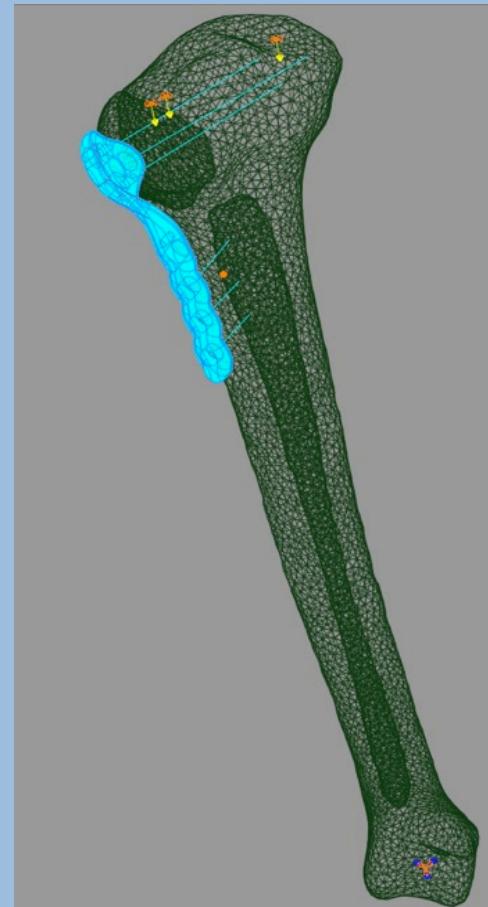
- > Screws modeled with beam elements
 - Circular section (radius 3.3mm)
 - Connection to the bone made with embedded elements



Finite Element Analysis

- > 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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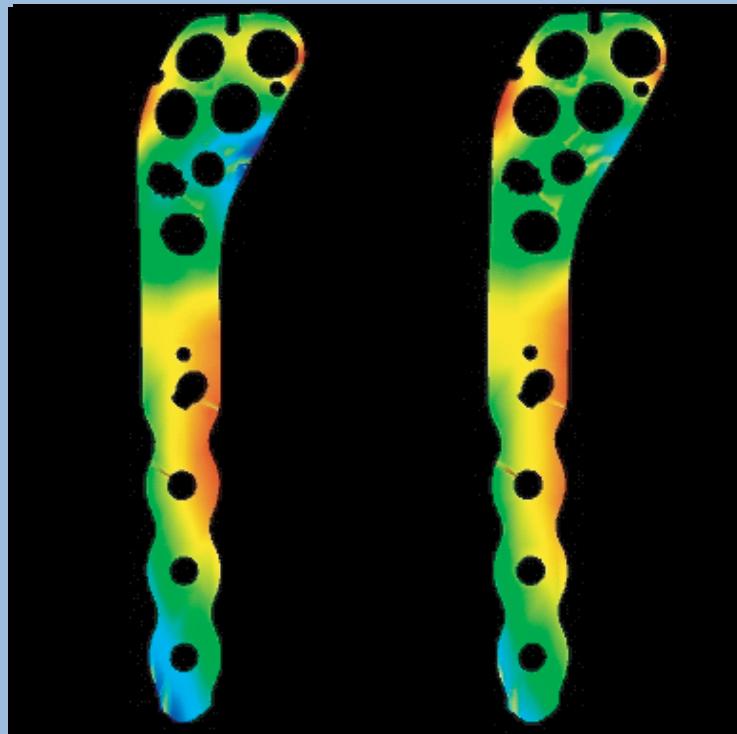
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Results: Asian/Caucasian distance maps

Average distance

Asian

Caucasian



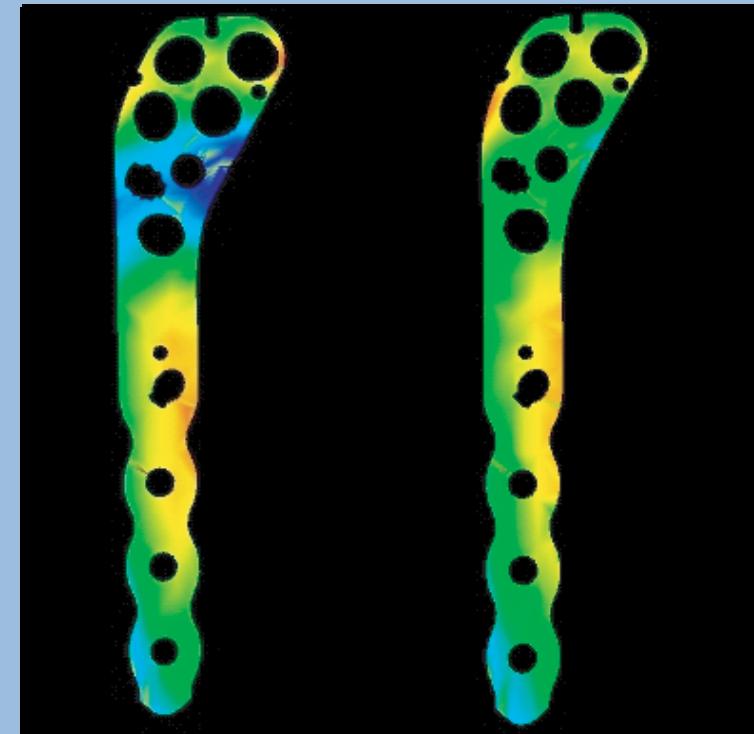
Range: 0 – 4 mm



Max. distance

Asian

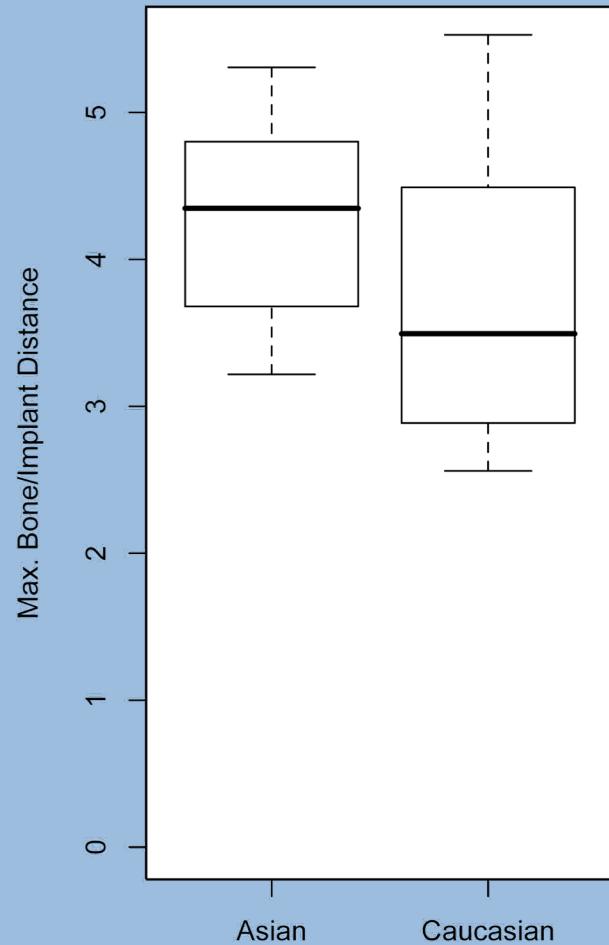
Caucasian



Range: 0 – 7 mm

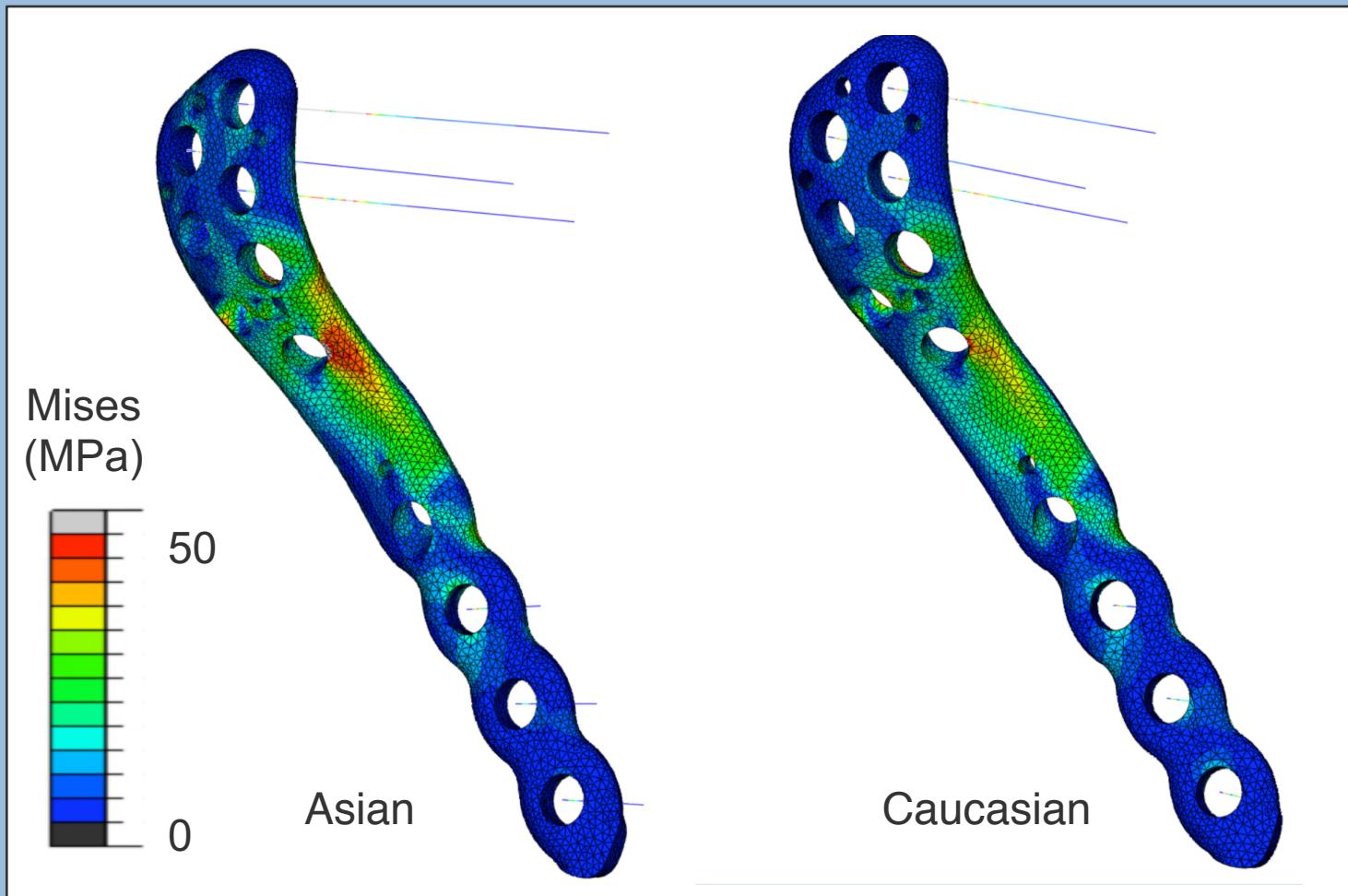


Results: Asian/Caucasian distance maps



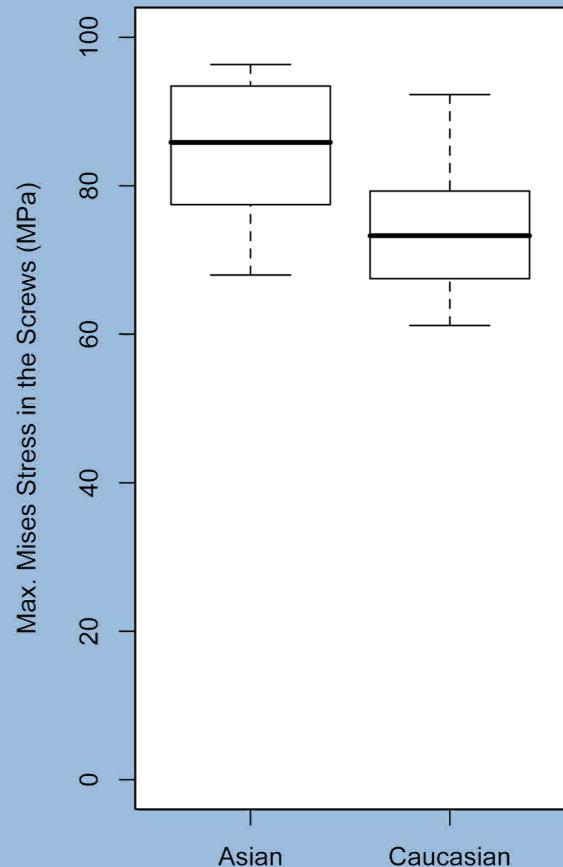
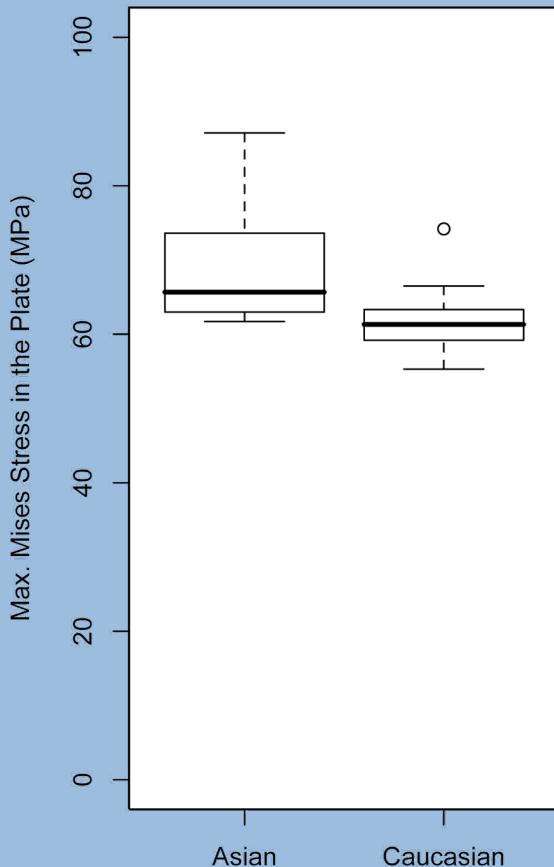
➤ No statistical differences
between Asian and Caucasian

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
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Thank you!