Cartilage Geometry Measurement and Visualization

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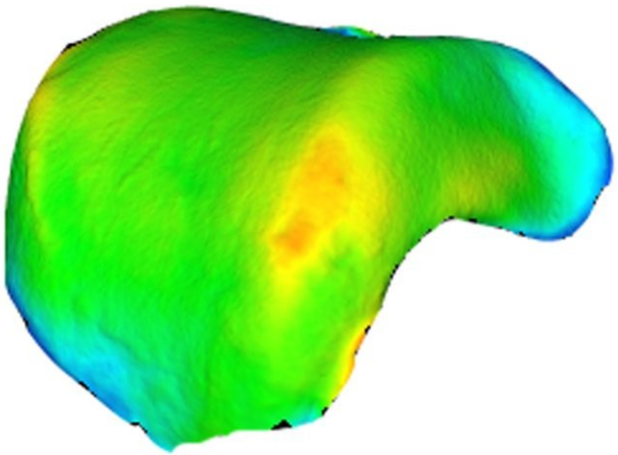
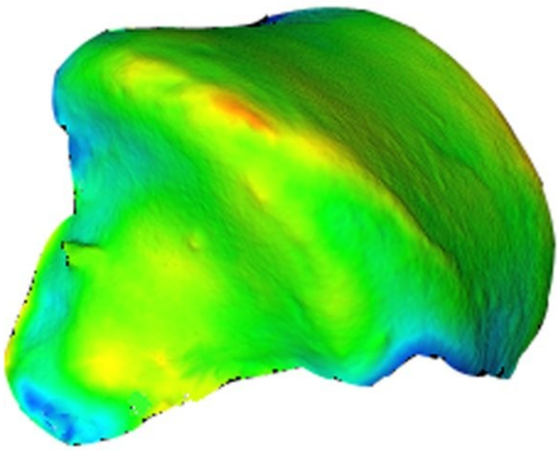




Motivation

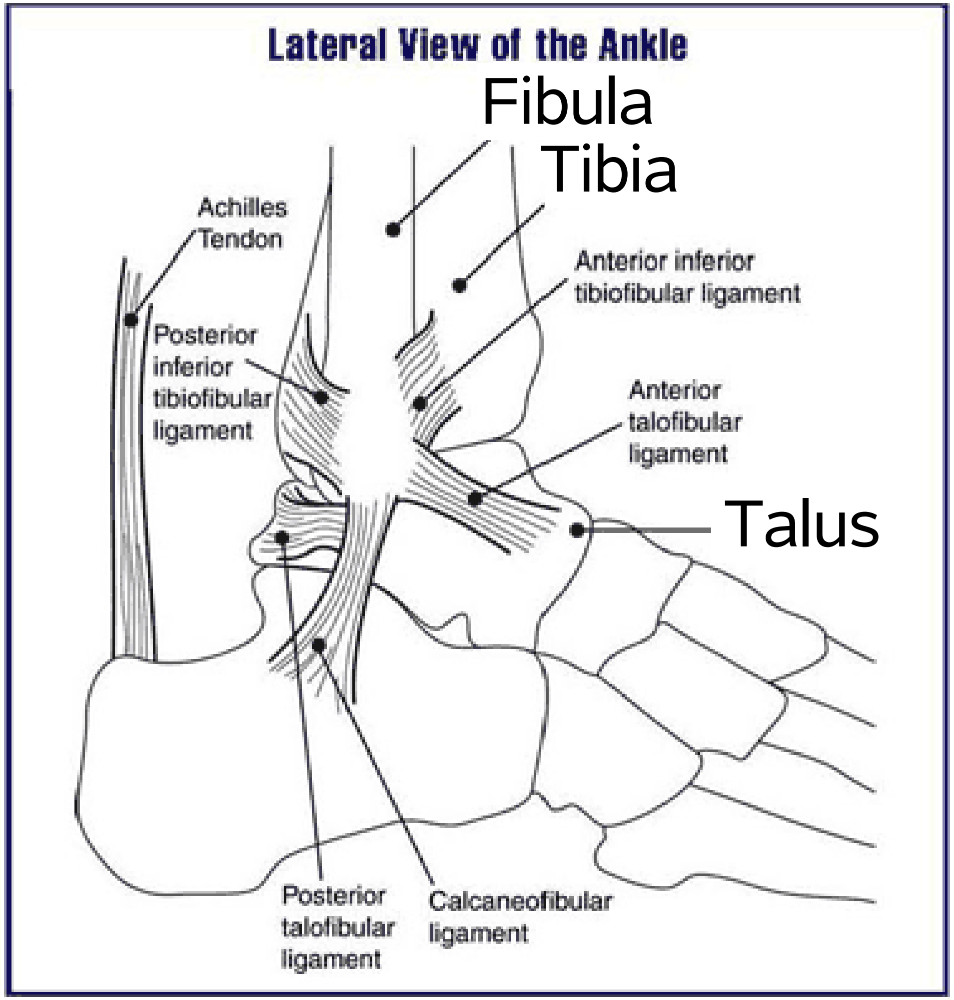
- Medical
  - Improved diagnosis $\longrightarrow$ better therapy
  - Highly accurate 3D measurement + tools
  - Evaluation of other methods (few for ankle joint)
- Technical
  - Case study
  - Processing framework for geometrical computations

Agenda

- Motivation
- Introduction
- Measurement procedures
- Related work
- Methods and examples
- Processing framework
- Performance and results
- Conclusions and future work

Introduction

- Geometry essential to understand biomechanics
- Previous methods:
  - Thickness: needle probe
  - Contact: Fuji film

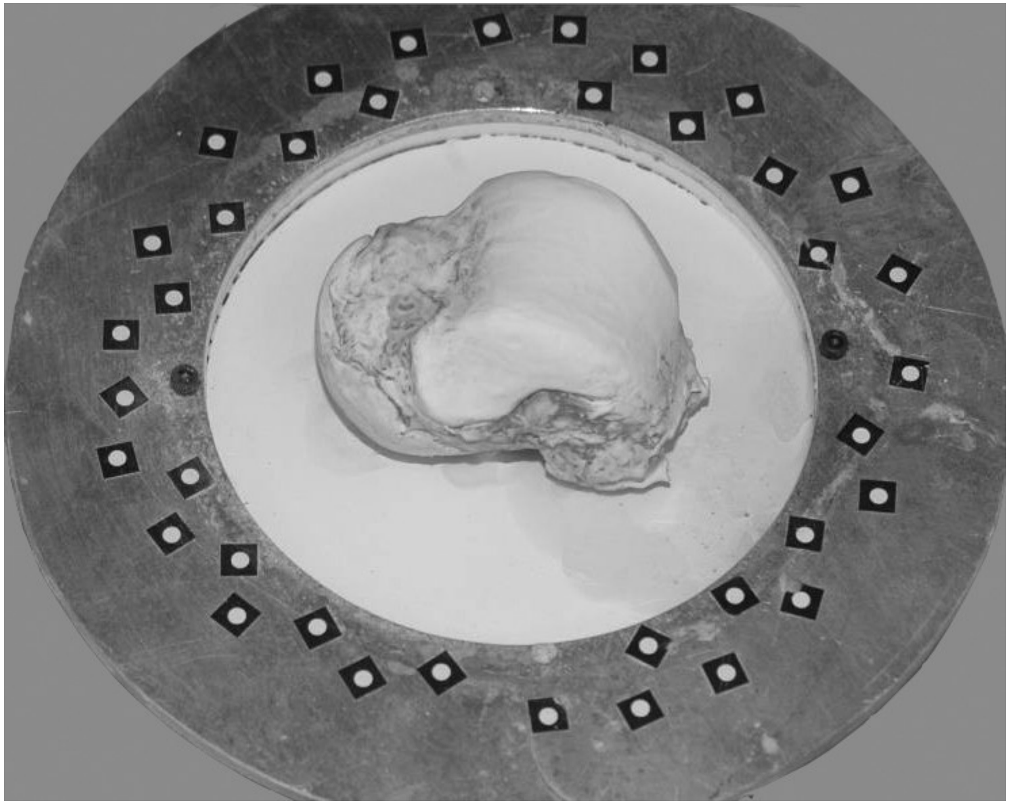


3D measurement technique

- ATOS (Advanced Topometric Sensor)
- Capture3D
- 2 cameras
- Grid projector
- Error ±2μm
- Problem: specular surface (powder)

Cartilage and bone surface

- Disarticulate joint
- Measure cartilage surface
- Dissolve cartilage (5% NaClO solution for 6-8 hours)
- Measure subchondral bone surface
- Register meshes with photo targets



Loading

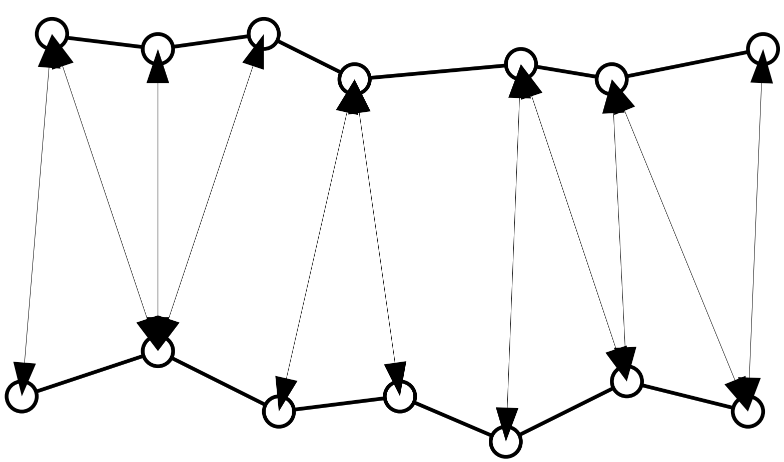
- Contact surface
- Load up to 1000 N
- Neutral
- 20° dorsiflexion, eversion, inversion, and plantarflexion

Related work and methods

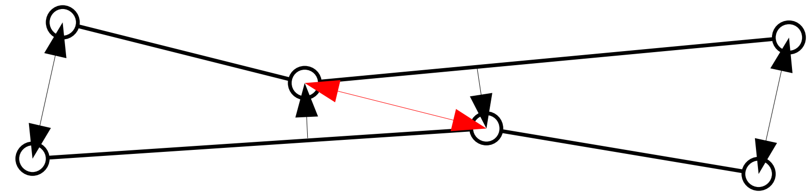
- Preprocessing
  - Distance computation and mesh cleanup
  - Hole filling
  - Mesh smoothing
  - Mesh stitching
- Geometric computations
  - Area
  - Volume
  - Thickness
  - Contact area

Distance computation

- Vertex-vertex vs. vertex-face
- Explicit Hausdorff distance [Aspert et al., 2002]
- Hierarchical search

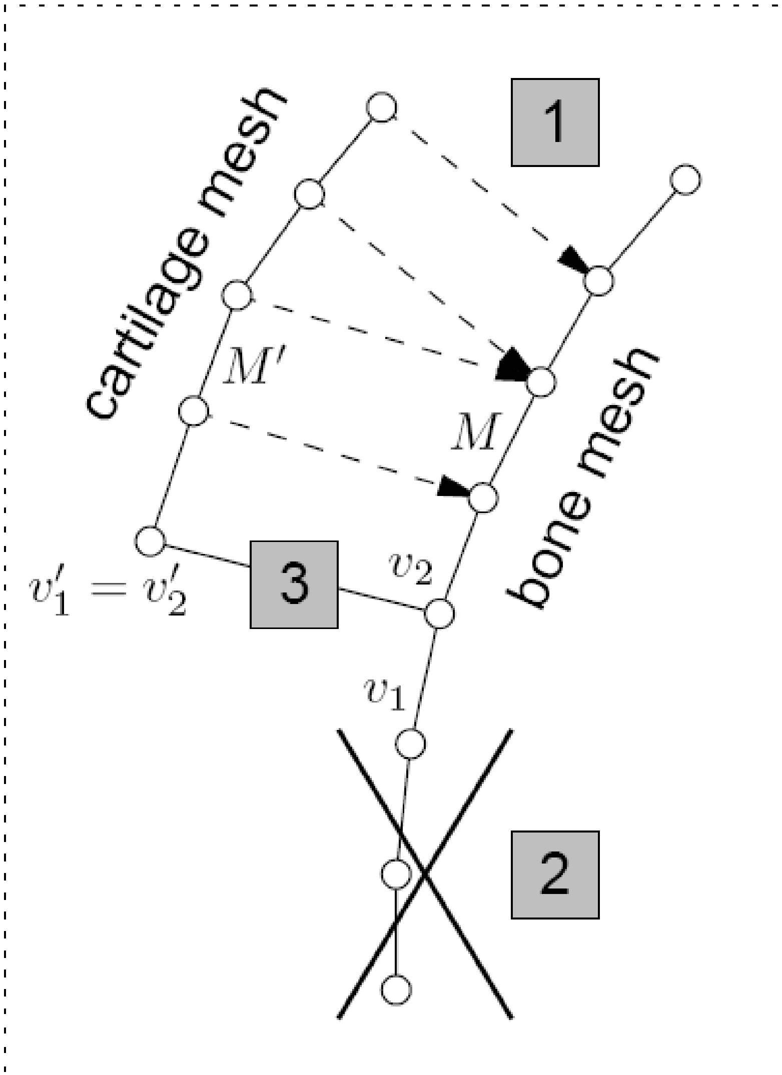


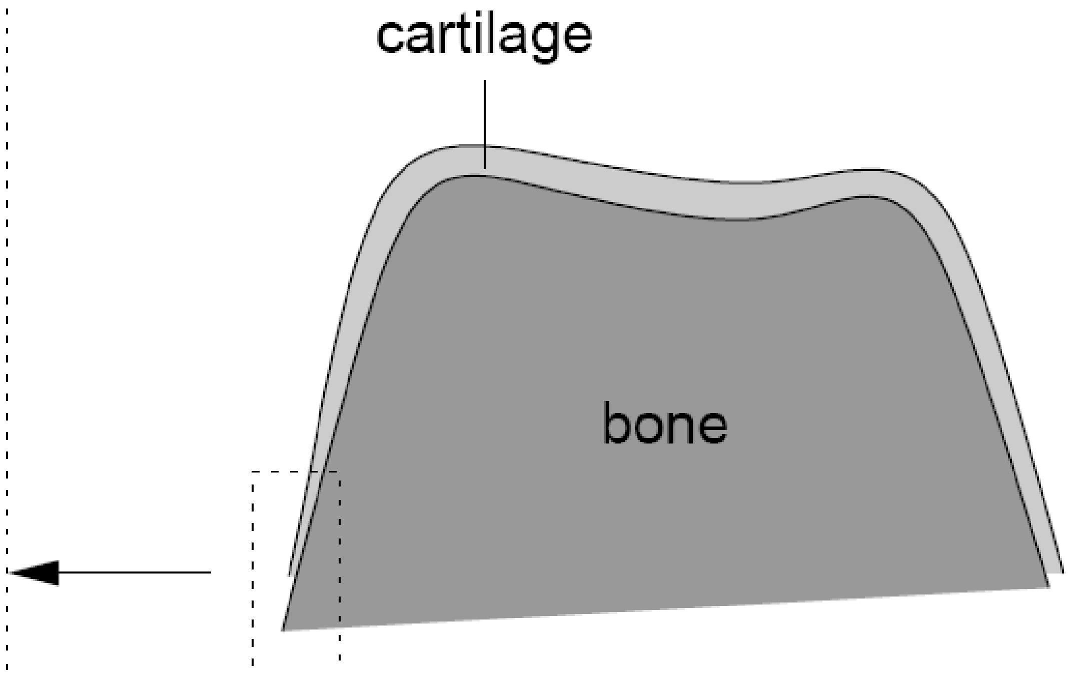
vertex-vertex



vertex-face

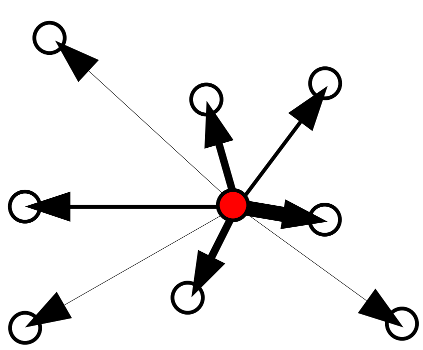
Mesh cleanup





Hole filling (1)

- Volumetric diffusion [Davis et al., 2003]
- Moving least squares
  [Wang et al., 2003; Tekumalla/Cohen, 2004]
  - Tradeoff adaptability vs. smoothness
  - Non-linear optimization of plane and biquadratic
  - Simpler solution: fix plane for entire hole to fill



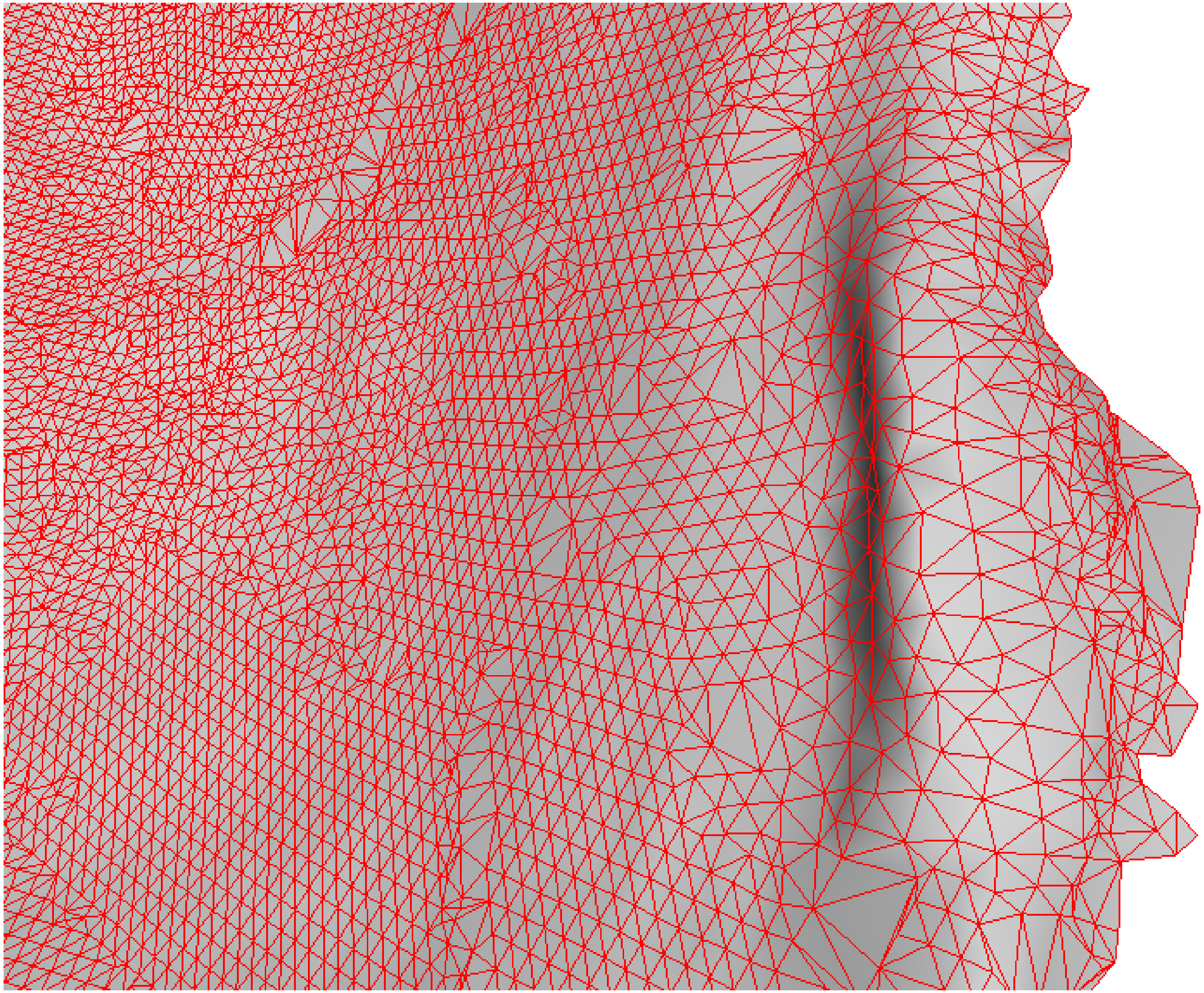
$$E_p(s) = \sum_{i=1}^{N} w_i(p)(s(p_i) - f_i)^2$$

fitted surface — given samples

Hole filling (2)

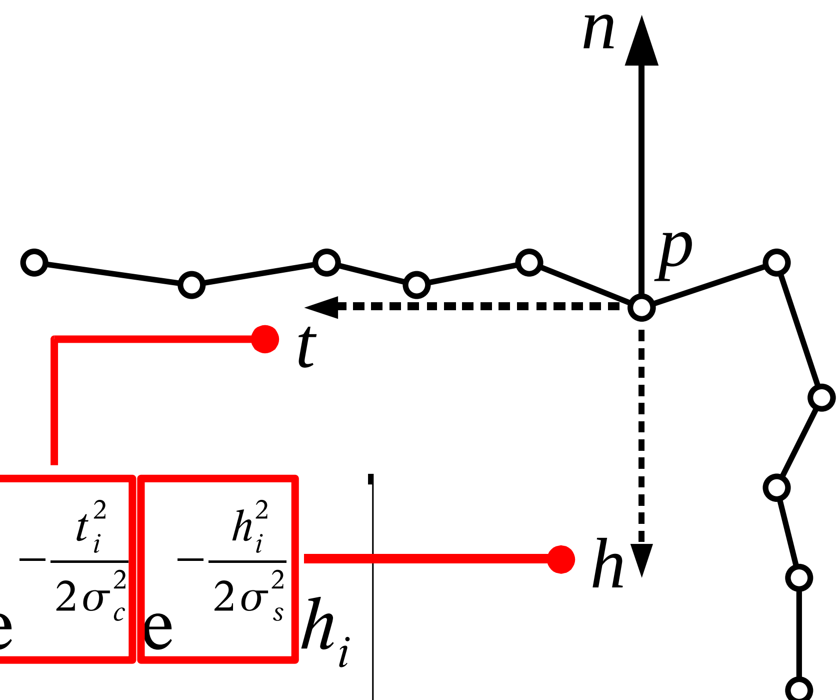
- Constrained Delaunay triangulation
  - Maximum size = twice average size on border
  - Minimum angle = 30°
- Fallback solution if projection of border is non-simple polygon

Hole filling example



Mesh smoothing

- Bilateral Mesh Denoising (Fleishman et al., 2003)
- Closeness vs. similarity
- Mesh shrinkage



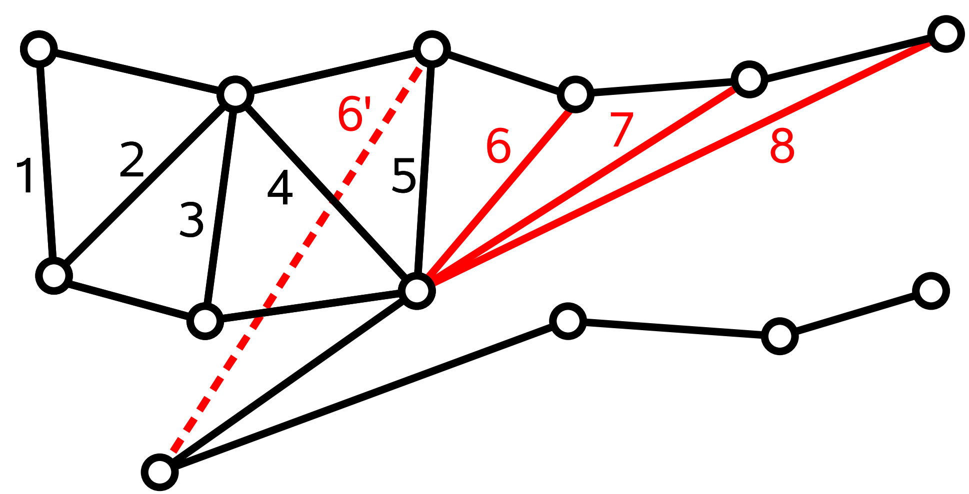
$$t_i = \|p - q_i\|$$

$$h_i = \langle n, p - q_i \rangle$$

$$p' = p + \left[\frac{\sum_{q_i \in N(p)} e^{-\frac{t_i^2}{2\sigma_c^2}} e^{-\frac{h_i^2}{2\sigma_s^2}} h_i}{\sum_{q_i \in N(p)} e^{-\frac{t_i^2}{2\sigma_c^2}} e^{-\frac{h_i^2}{2\sigma_s^2}}} \right] n$$

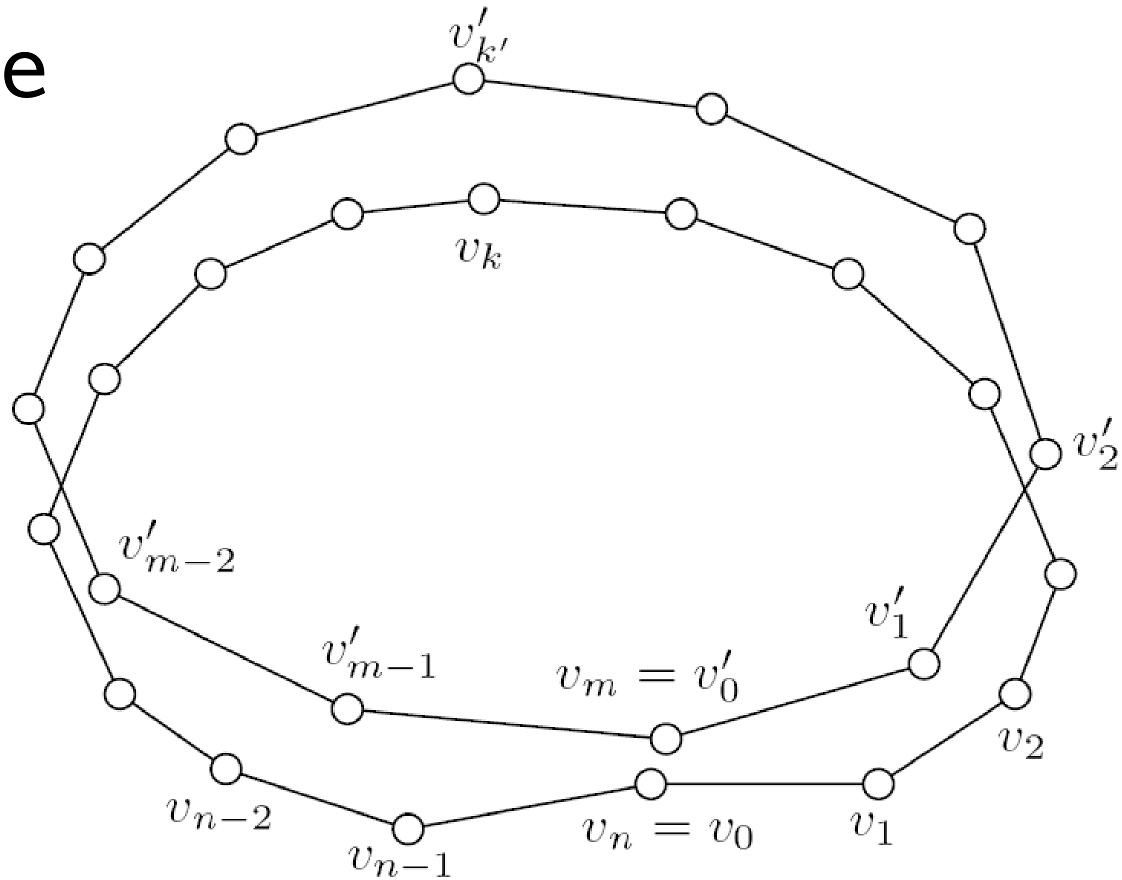
Mesh stitching

- From range images [Turk/Levoy, 1994]
- Finite elements [Field, 2001]
- Two polygons in 3D (not necessarily parallel)
- Greedy stitching: always select shorter edge

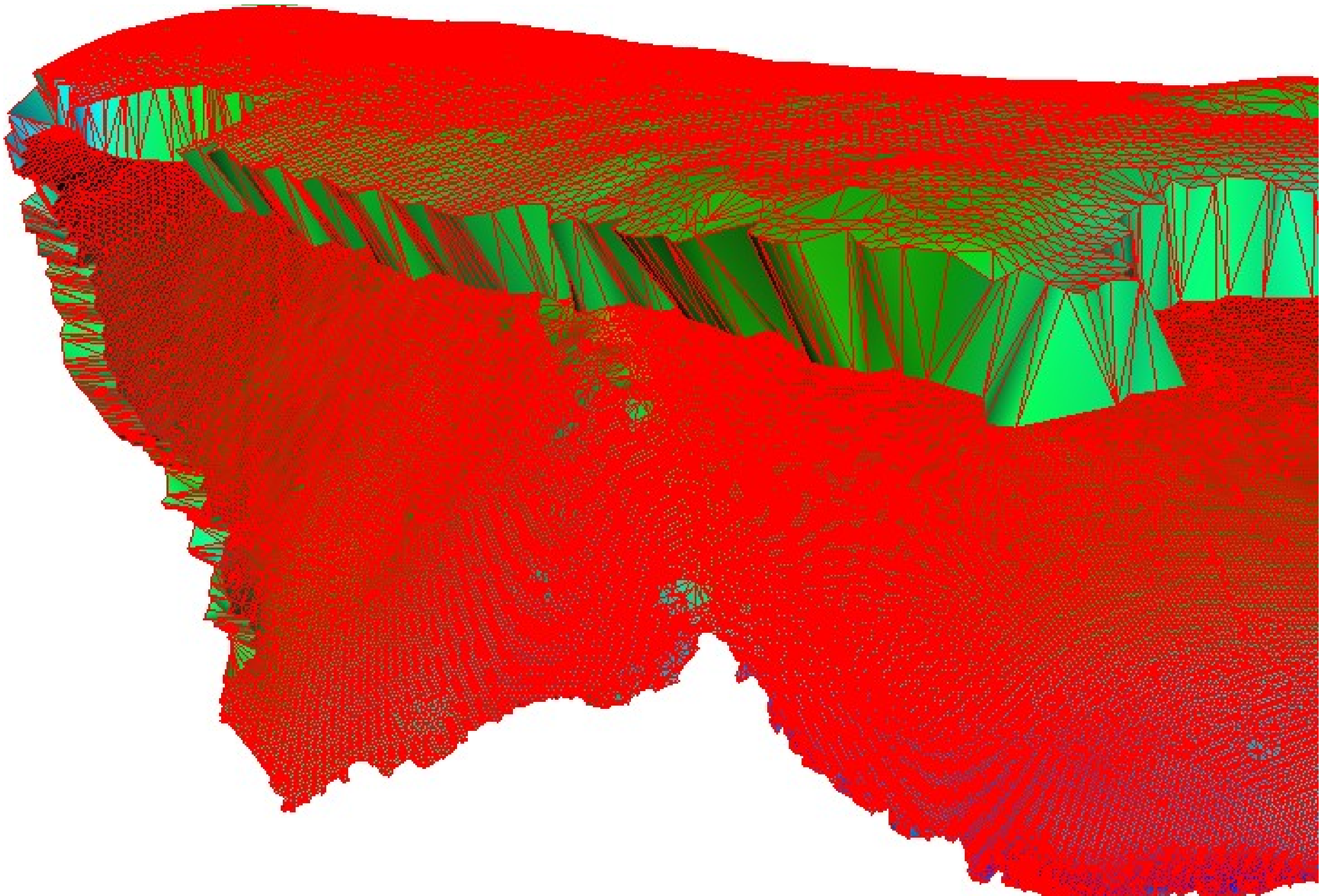


Hierarchical mesh stitching

- Recursively subdivide longer polyline
- Find closest vertex on shorter polyline
- Create 1 or 2 triangles if 3 or 4 points left

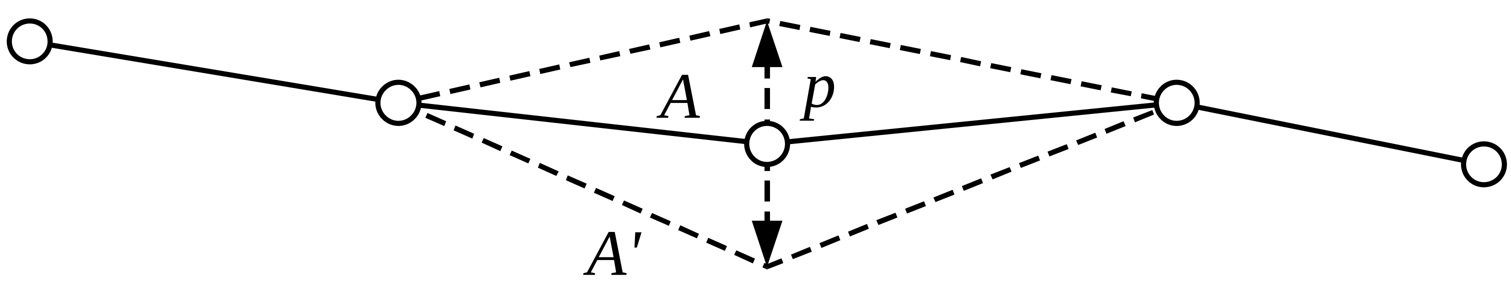


Mesh stitching example



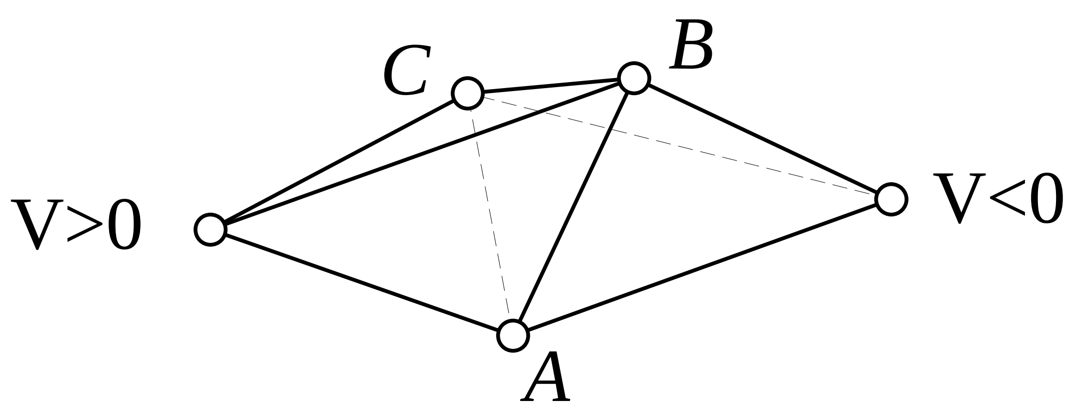
Area

- Trivial: sum of triangle areas
- Low sensitivity to noise



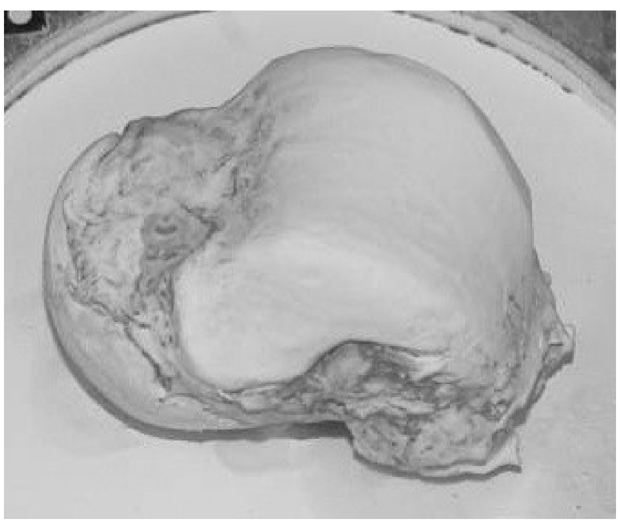
Volume

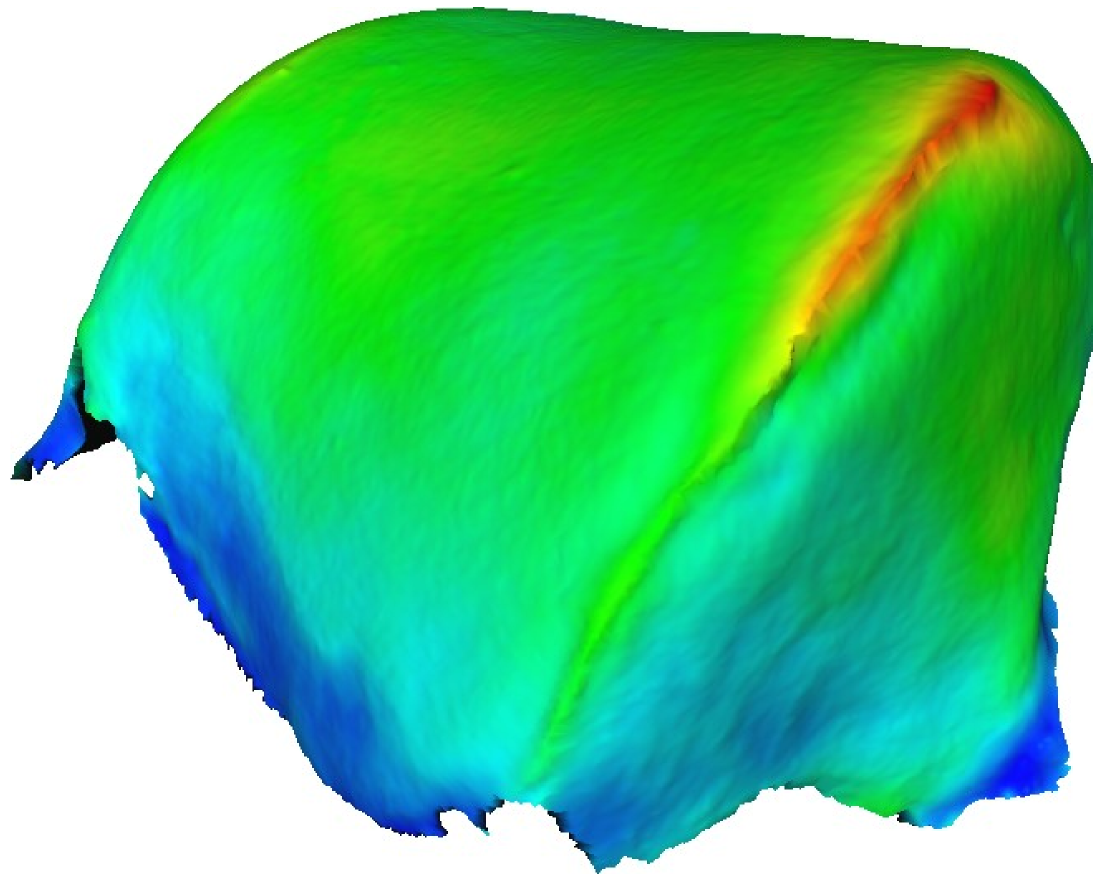
- Sum of signed volumes of tetrahedra composed of surface triangles and fixed reference point
- Center of gravity for numerical stability
- Two-manifold mesh without boundary
- Very low sensitivity to noise



Thickness

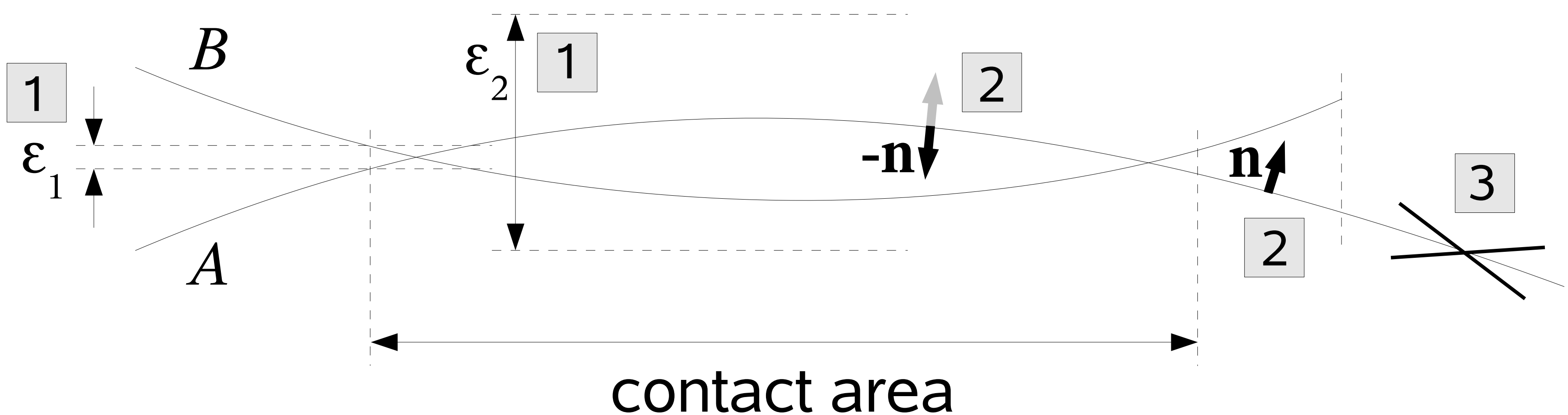
- Precomputed distance
- Color encoding
- Average thickness = volume / area





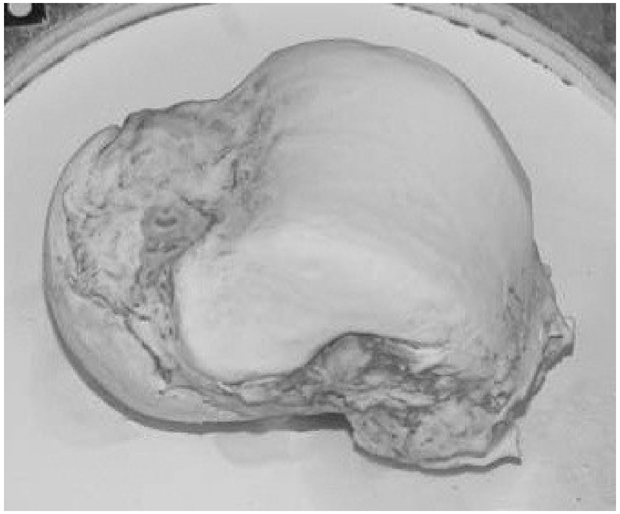
Contact area

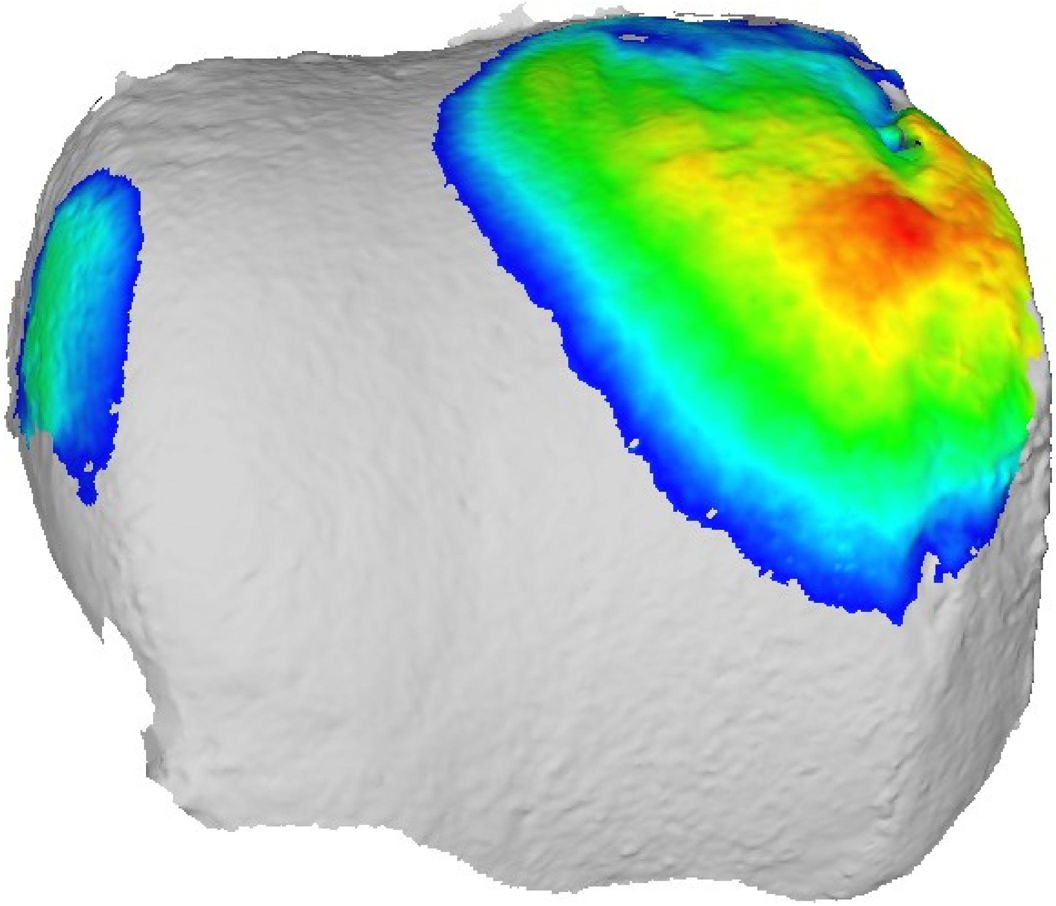
- Winkler elastic foundation model [Johnson, 1985]
- Heuristic:
  - non-overlapping, distance < ε_1 → contact
  - overlapping, distance < ε_2 → contact
  - remove non-corresponding regions



Contact area example

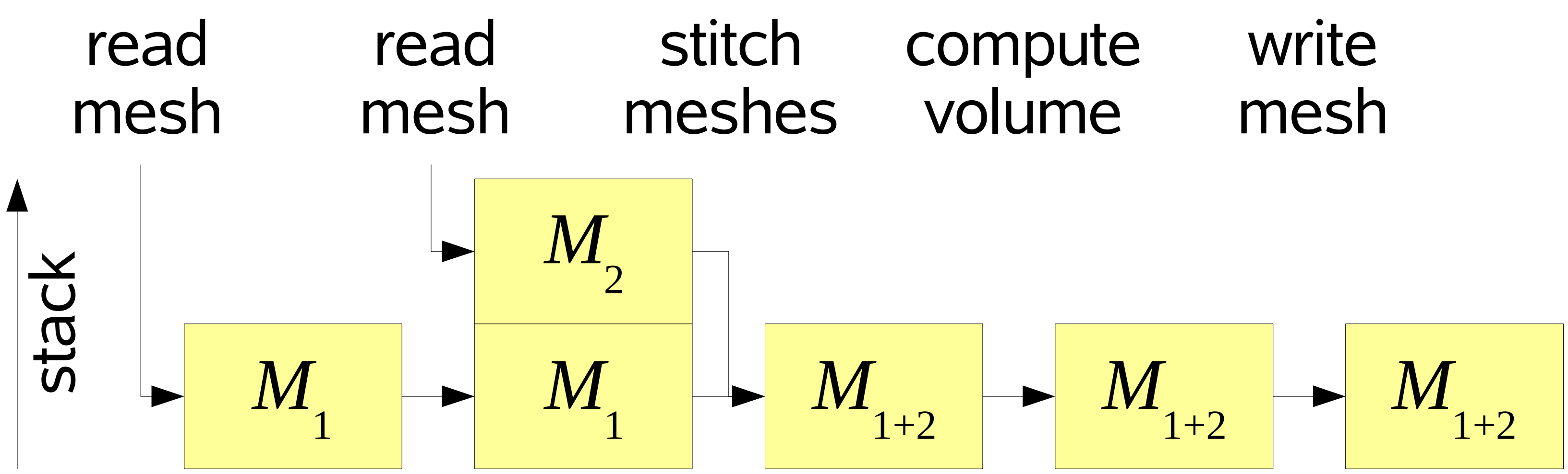
- Color code is amount of overlap
- Identify stressed regions





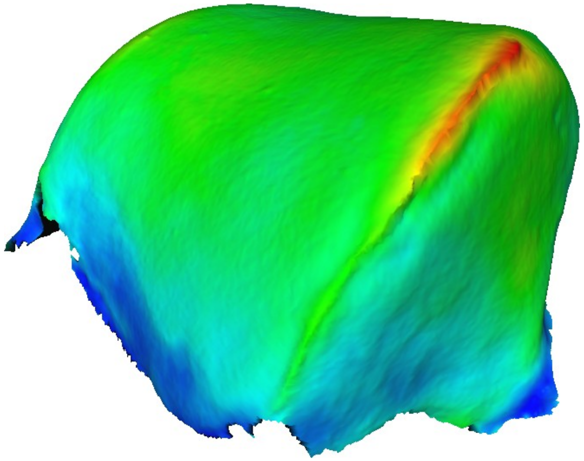
Processing framework

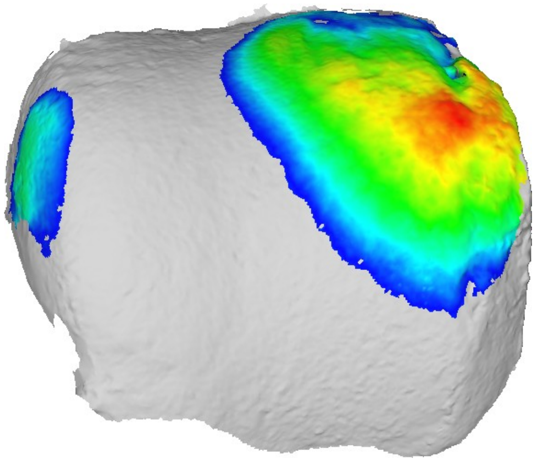
- Mesh stack and operations
- File input → push mesh
- Computation → pop mesh
- Example:



Performance

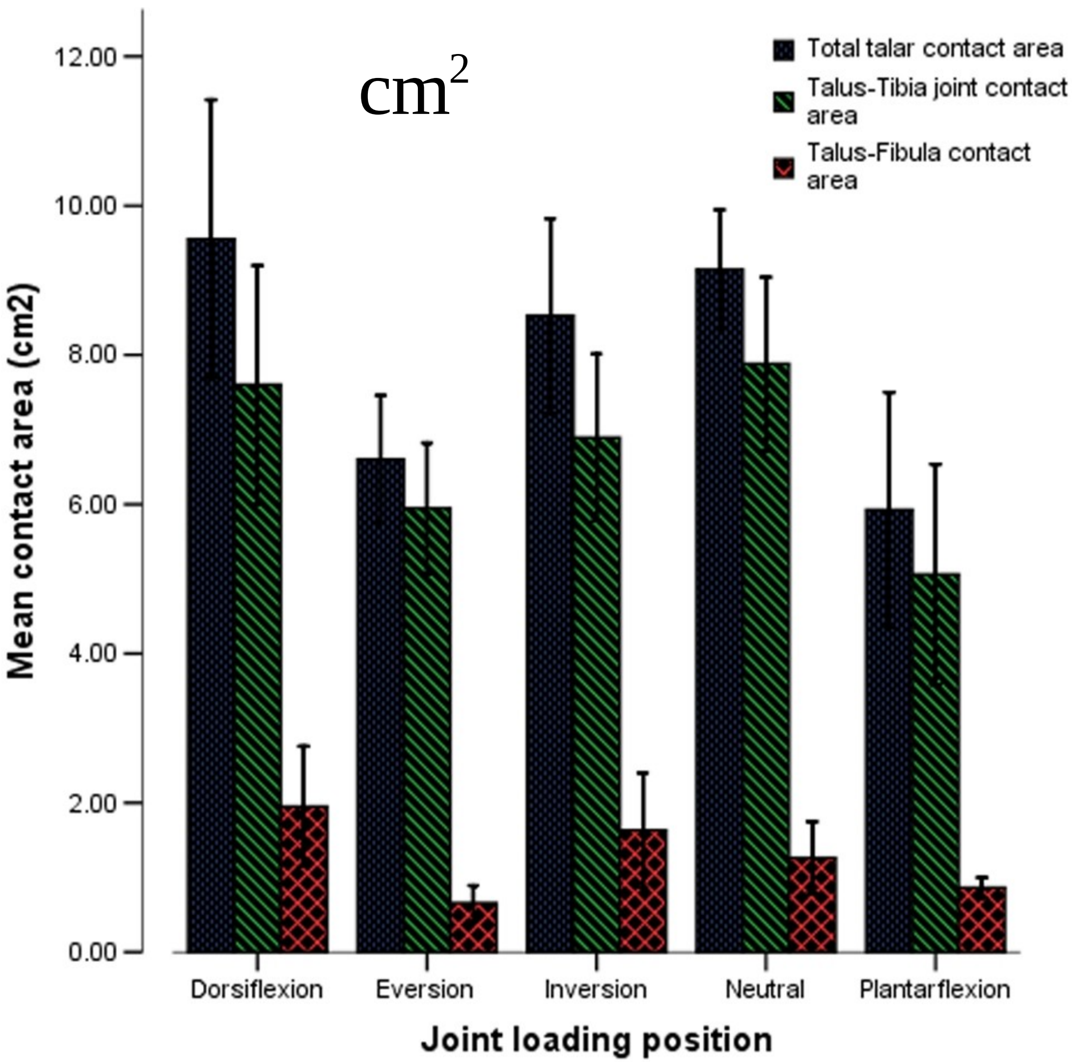
- Intel Core 2 duo
- 2.13GHz
- 2GB RAM
- Single-threaded

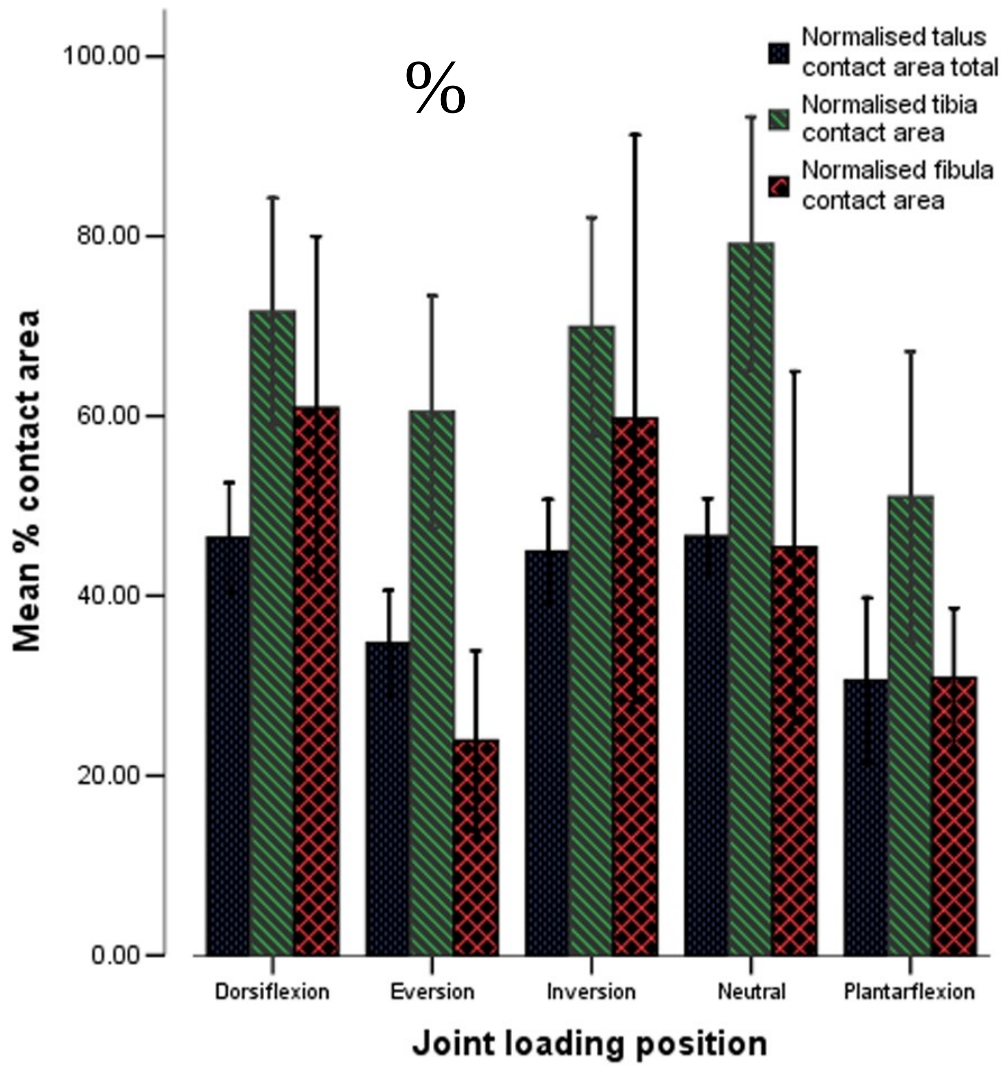




experiment	mesh size	processing time
compute talus cartilage area, volume, and thickness map	139 kT 158 kT	21 sec
compute talus/tibia dorsiflexion contact area	159 kT 97 kT	15 sec

Results


cm2
Total talar contact area
Talus-Tibia joint contact area
Talus-Fibula contact area
Mean contact area (cm2)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Dorsiflexion
Eversion
Inversion
Neutral
Plantarflexion
Joint loading position


%
Normalised talus contact area total
Normalised tibia contact area
Normalised fibula contact area
Mean % contact area
100.00
80.00
60.00
40.00
20.00
0.00
Dorsiflexion
Eversion
Inversion
Neutral
Plantarflexion
Joint loading position

Conclusions

- Comparison with existing methods
  - Highly accurate (according to specification)
  - Confirms results for low curvature regions
  - Rejects results for high curvature regions
- Convenient framework for computation
- Sufficient performance

Future work

- Compare with MRI data
- Apply method to other joints
- Measure mechanical data
  - Stiffness, deformation
  - Haptic feedback application
  - Surgery training

Thank you for your attention!