FACULTY
OF APPLIED SCIENCES
UNIVERSITY
OF WEST BOHEMIA

MEDICAL INFORMATICS
UNIVERSITY OF WEST BOHEMIA

Challenges in Musculoskeletal Modelling

Josef Kohout / besoft@kiv.zcu.cz

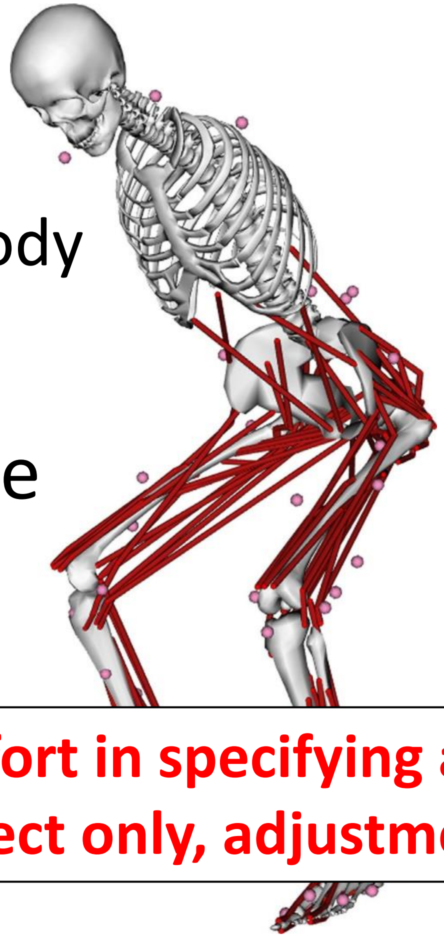
Background

- Musculoskeletal modelling used for various tasks
  - preoperative orthopaedic surgical planning
  - postoperative assessment in orthopaedic surgery
  - rehabilitation procedures
  - prosthesis design
  - prevention of injuries in professional sport
  - etc.
- Most of these tasks require patient-specific models

Background

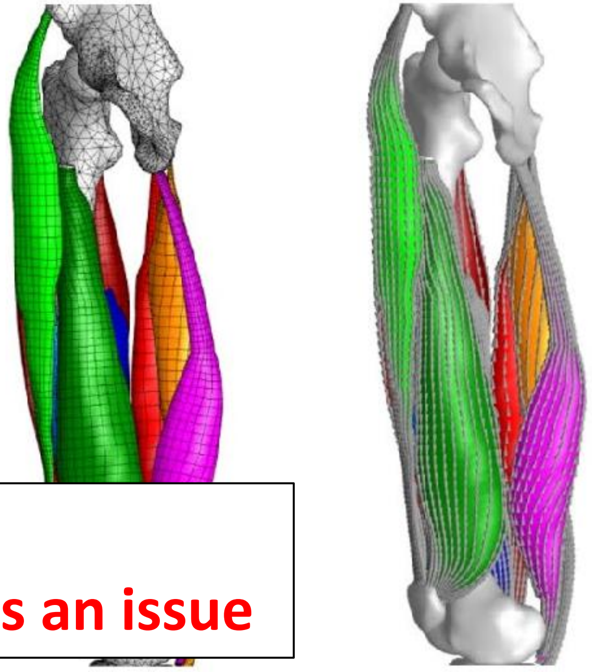
classical models representing a muscle by a set of lines (fibres)

- commercially used
  - e.g., OpenSim, AnyBody
- real-time simulations
- limited muscle-muscle and muscle-bone interactions



research models representing a muscle by a FEM mesh

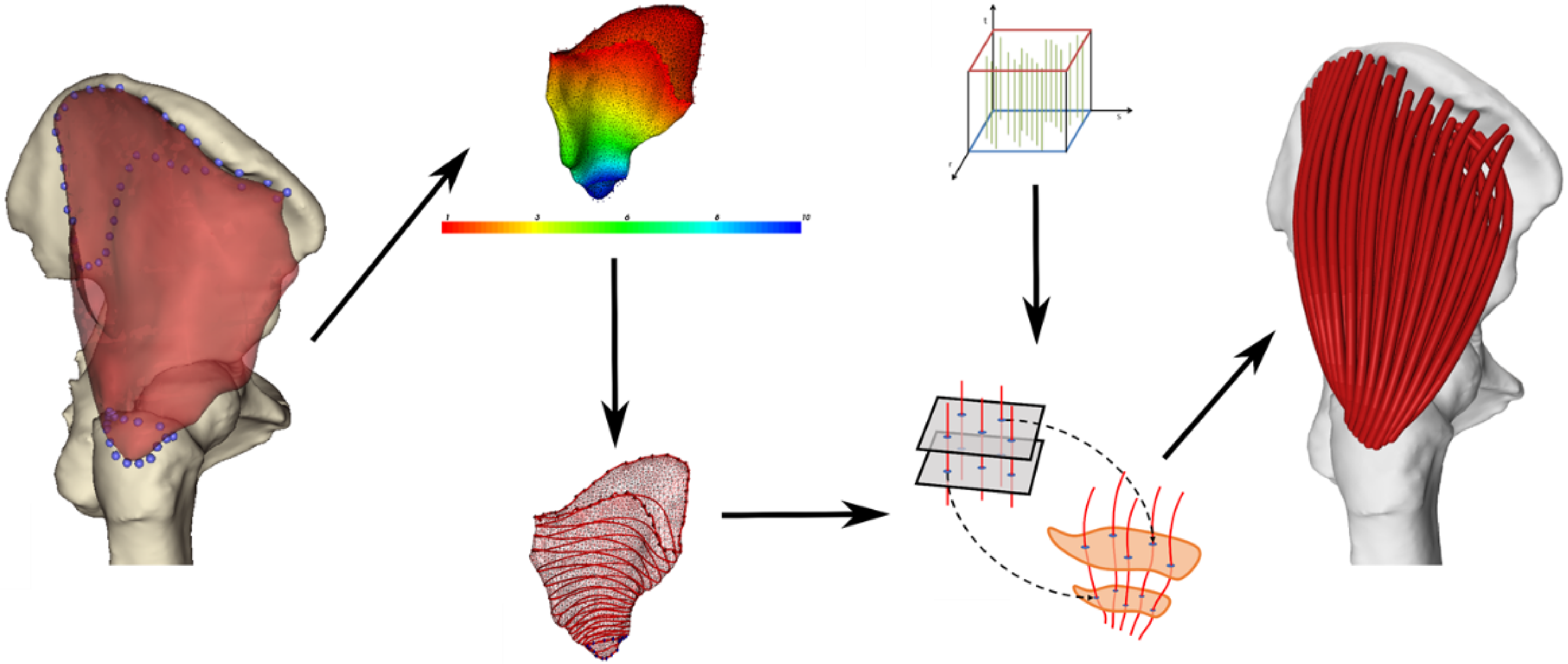
- simulations on supercomputers
- considered to be accurate
- often tricky to setup



significant manual effort in specifying attachments and constraints
valid for a single subject only, adjustments to the concrete patient is an issue

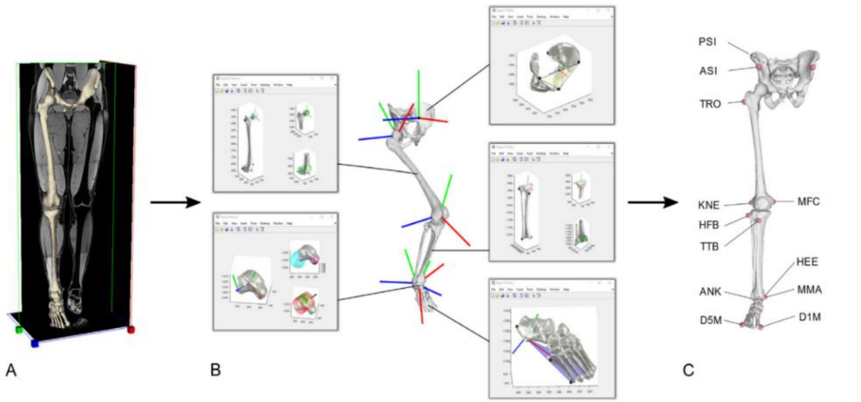
Our goal

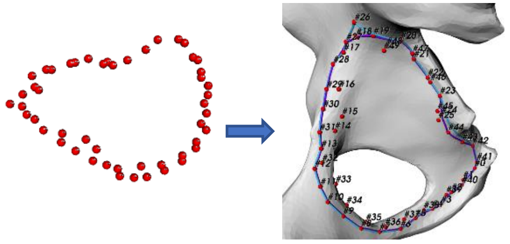
- **We aim at fully automated construction of a patient-specific musculoskeletal model combining advantages of both worlds**



1

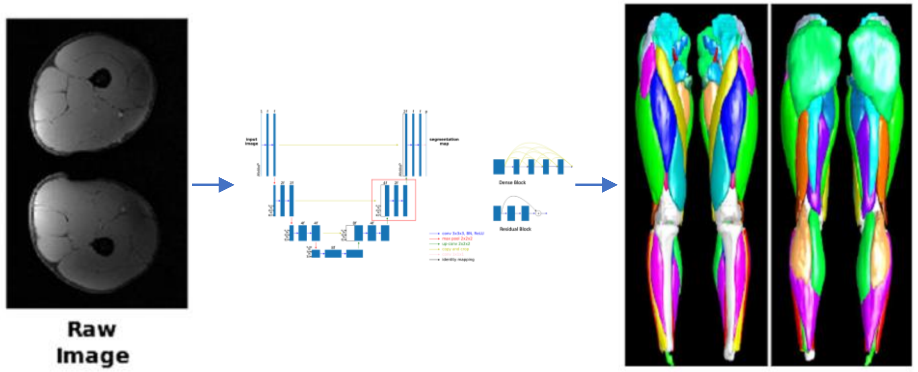
Workflow

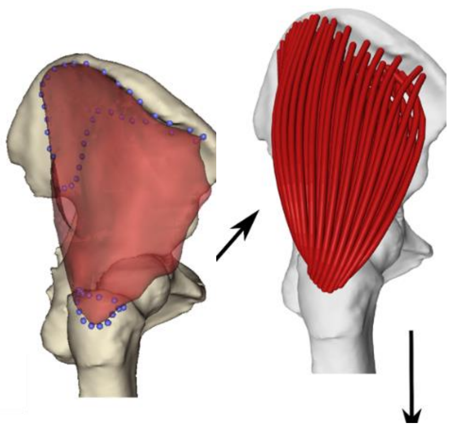


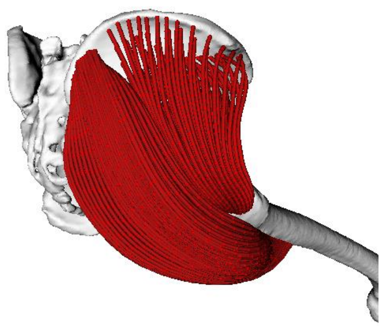


Motion Data

Create models of bones and joints → Create surface models of muscles → Create attachment areas of the muscles → Decompose muscles into fibres → Deform muscles → Update the fibres paths



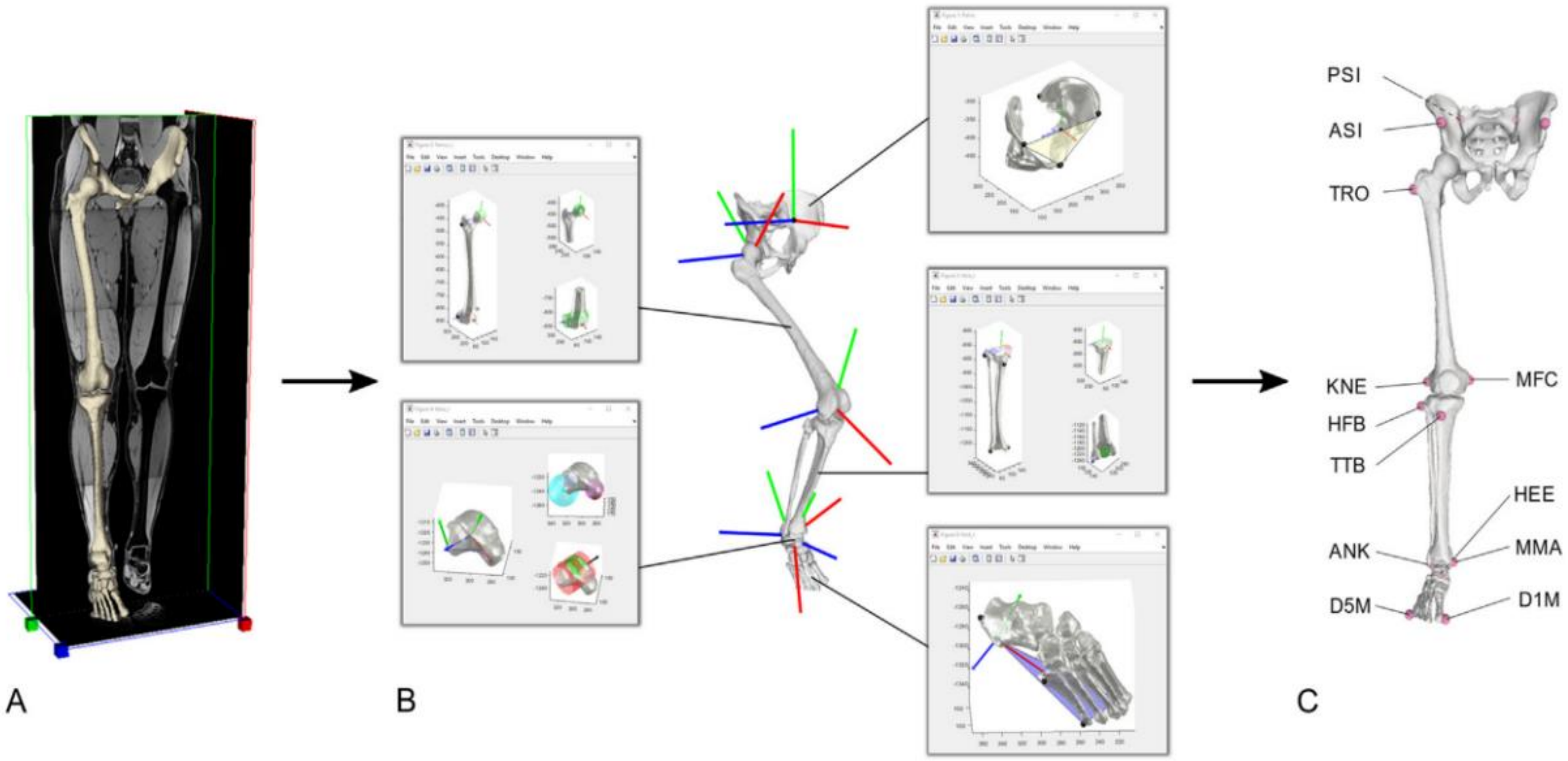




Create models of bones and joints

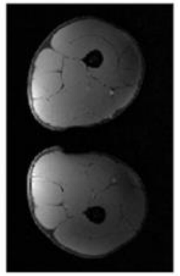
- Common process in all musculoskeletal modelling approaches
- Surface models of bones can be extracted automatically from CT/MRI
- Joints automatically estimated using recently developed tool STAPLE

Modenese, L., & Renault, J. (2021). Automatic generation of personalised skeletal models of the lower limb from three-dimensional bone geometries. *Journal of Biomechanics*, *116*, 110186. https://doi.org/10.1016/j.jbiomech.2020.110186

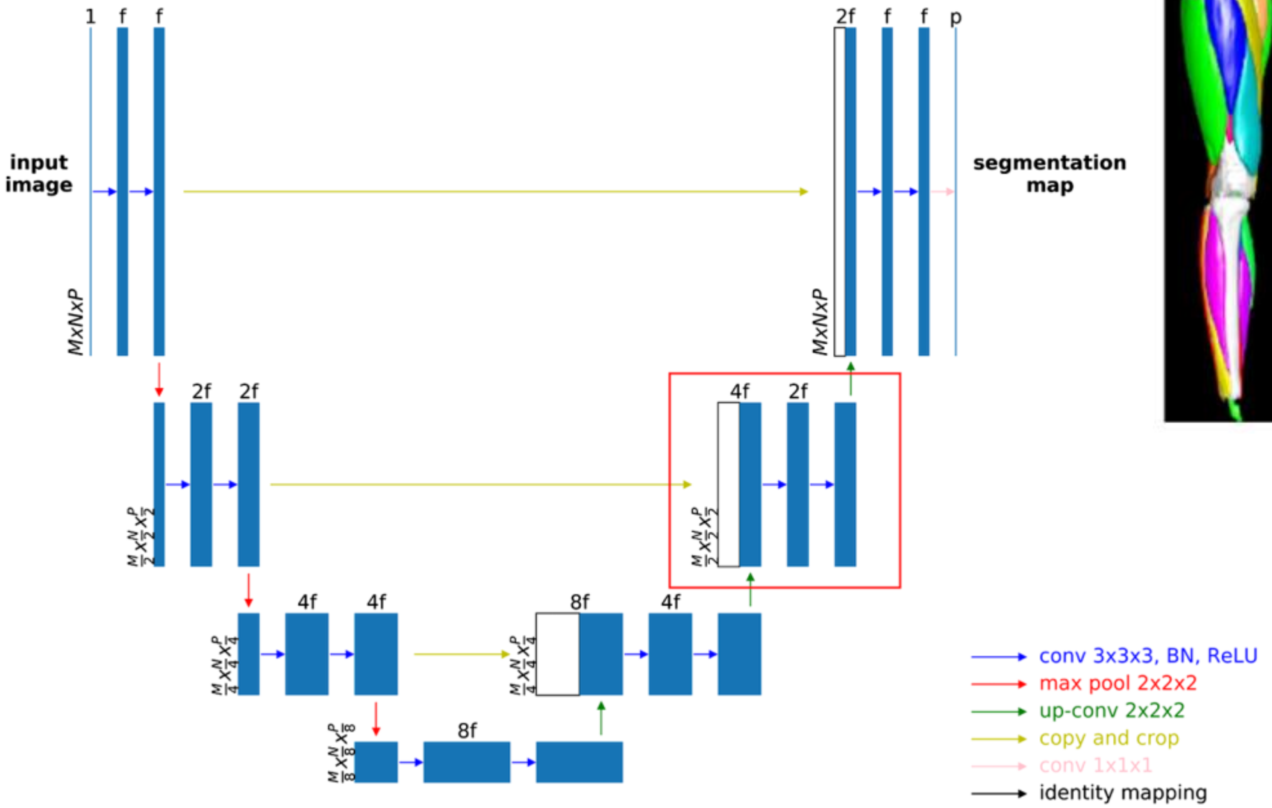


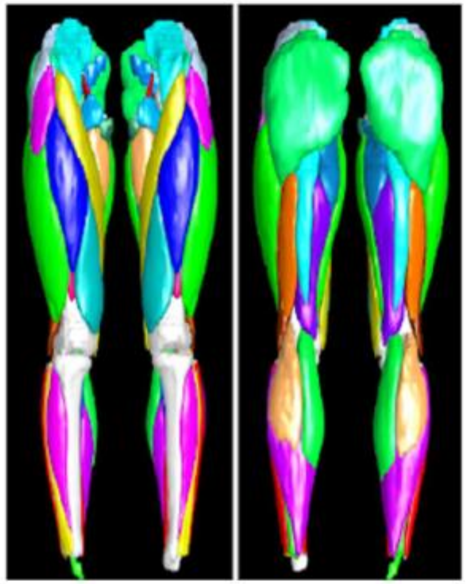
Create surface models of muscles

- Quite a challenge in the past since muscles/tendon boundaries are not well apparent in medical images
- Not an issue anymore with AI
  - At least theoretically



Raw Image

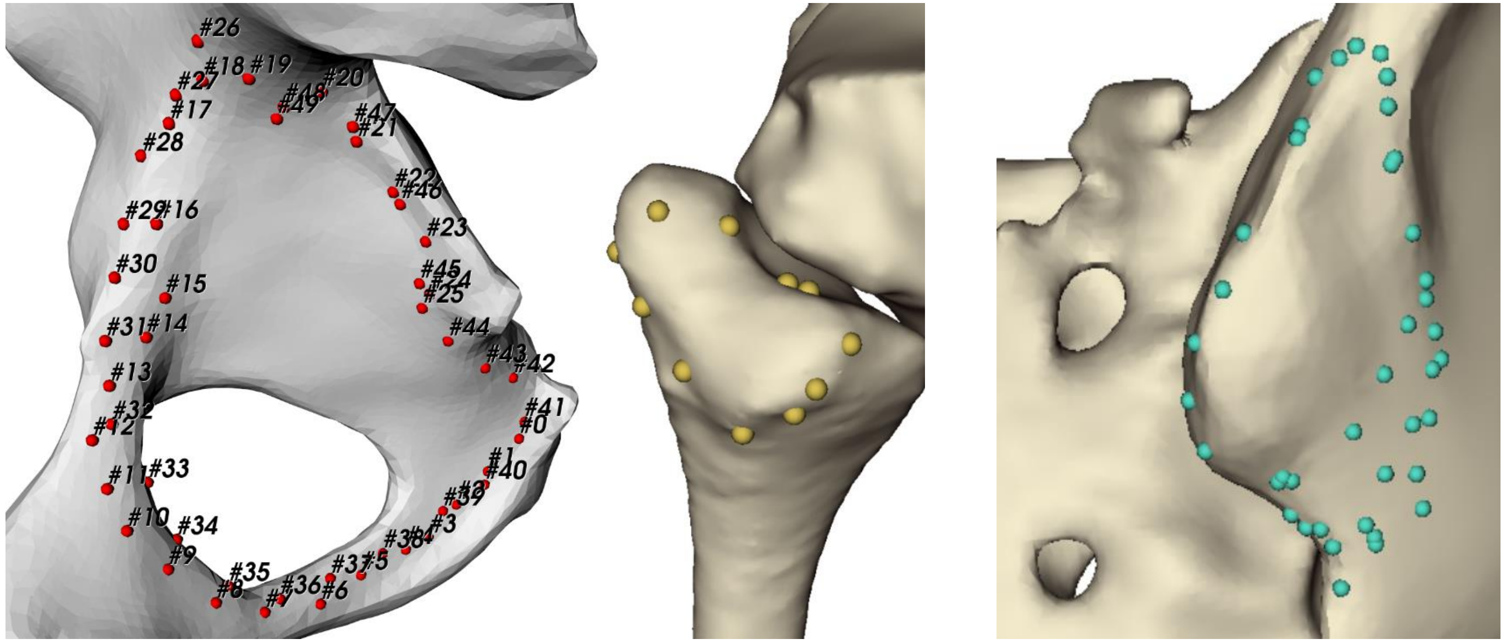




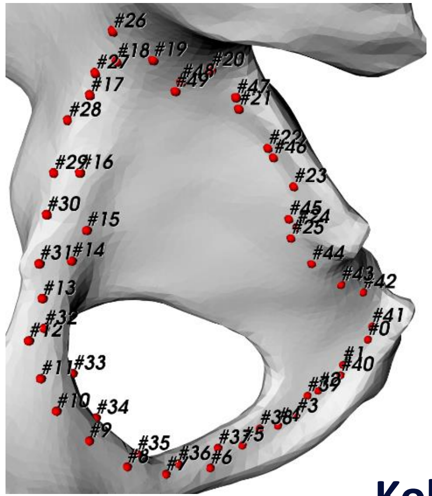
Ni, R., Meyer, C. H., Blemker, S. S., Hart, J. M., & Feng, X. (2019). Automatic segmentation of all lower limb muscles from high-resolution magnetic resonance imaging using a cascaded three-dimensional deep convolutional neural network. *Journal of Medical Imaging*, *6*(04), https://doi.org/10.1117/1.jmi.6.4.0440(

Create attachment areas of the muscles

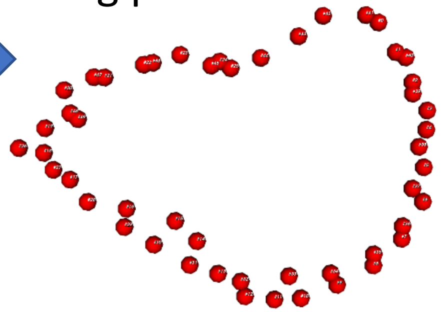
- No (automatic) method for extraction of the attachment areas from the medical images
- Attachment points commonly specified manually
  - points are unordered,
  - sparsely sampled,
  - and subject to various errors



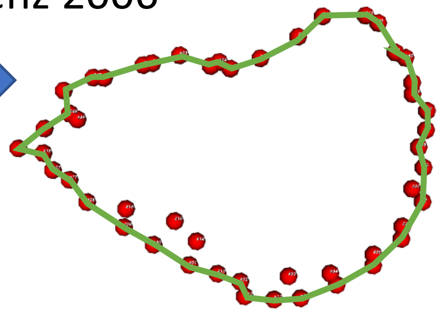
Create attachment areas of the muscles



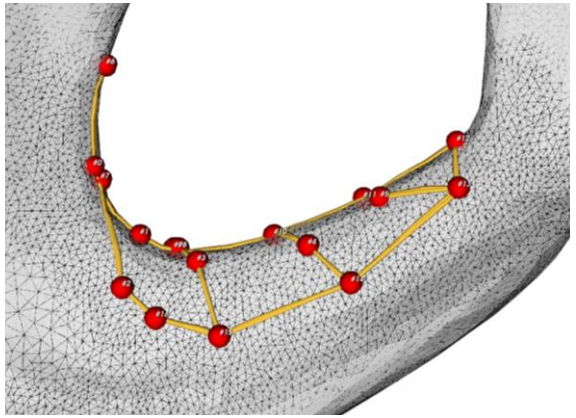
Project the points onto the best-fitting plane



Reconstruct 2D curves using Lenz 2006

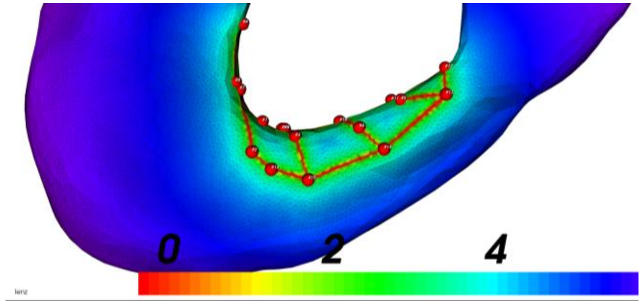


Calculate geodetics using fast marching (Peyré, 2009)

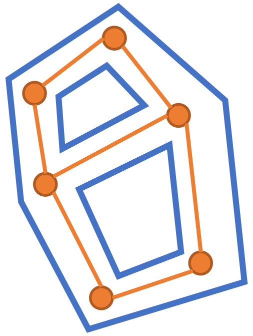


Kohout, J., & Cervenka, M. (2022). Non-planar Surface Shape Reconstruction from a Point Cloud in the Context of Muscles Attachments Estimation. ***Proceedings of the 17th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications*****. https://doi.org/10.5220/0010869600003124**

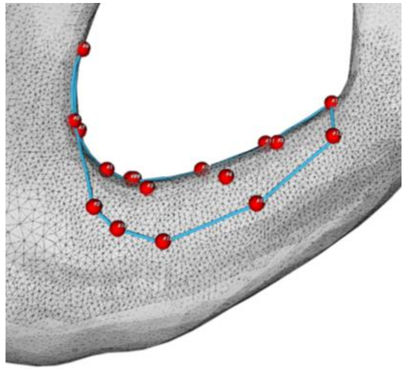
Compute the scalar field encoding the geodetic distance to these geodetics



Extract the iso-contour with the value → 0



Keep the component with the largest perimeter



Create attachment areas of the muscles

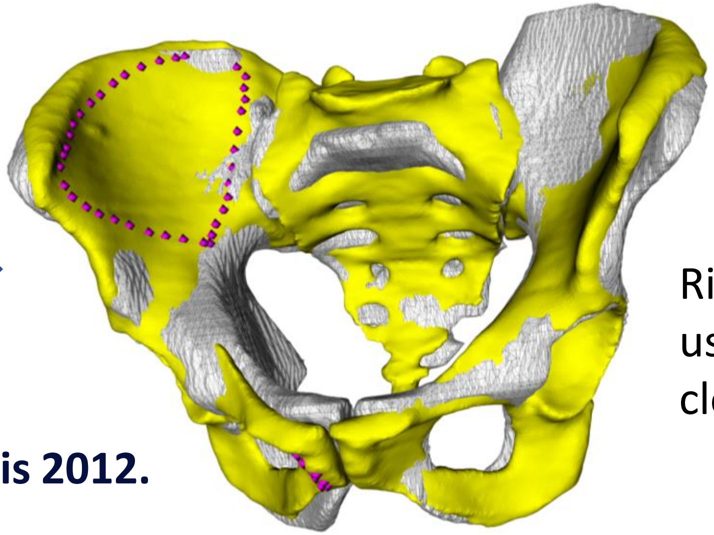
- **Challenge**: Can we estimate the attachment areas without specifying the attachment points manually?
- We could perform a non-rigid registration of a bone with attachment areas specified to the corresponding patient’s bone

Create attachment areas of the muscles

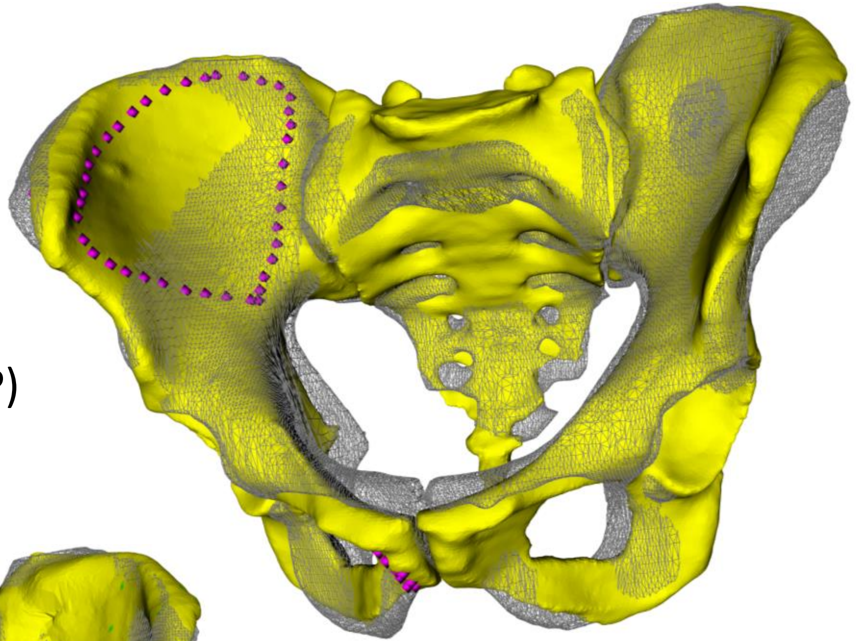
Translate, rotate and scale the source mesh to align it with the target mesh using PCA

Kellnhofer, P. Automatic mesh transformation method for musculoskeletal model. Master thesis 2012.

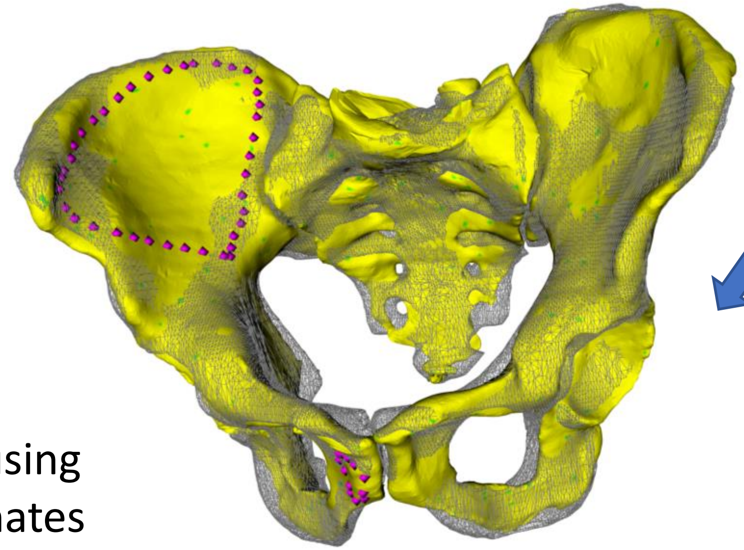
Kohout, J. et al. *Not published yet.*



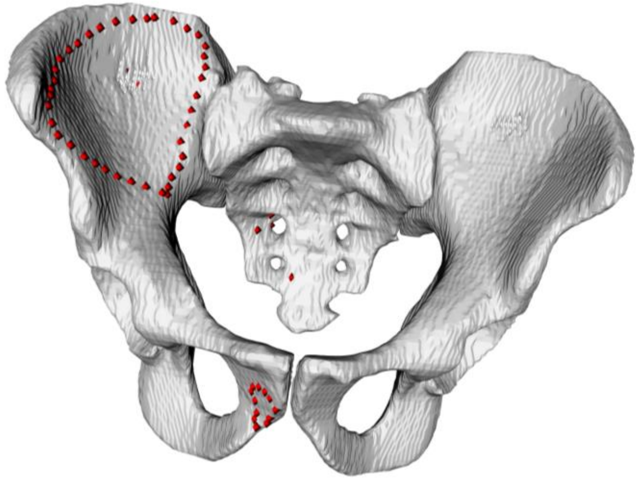
Rigid registration using iterative closest points (ICP)



Non-rigid registration using ICP on smaller patches of the mesh



Transforming the attachment areas using barycentric coordinates



Create attachment areas of the muscles

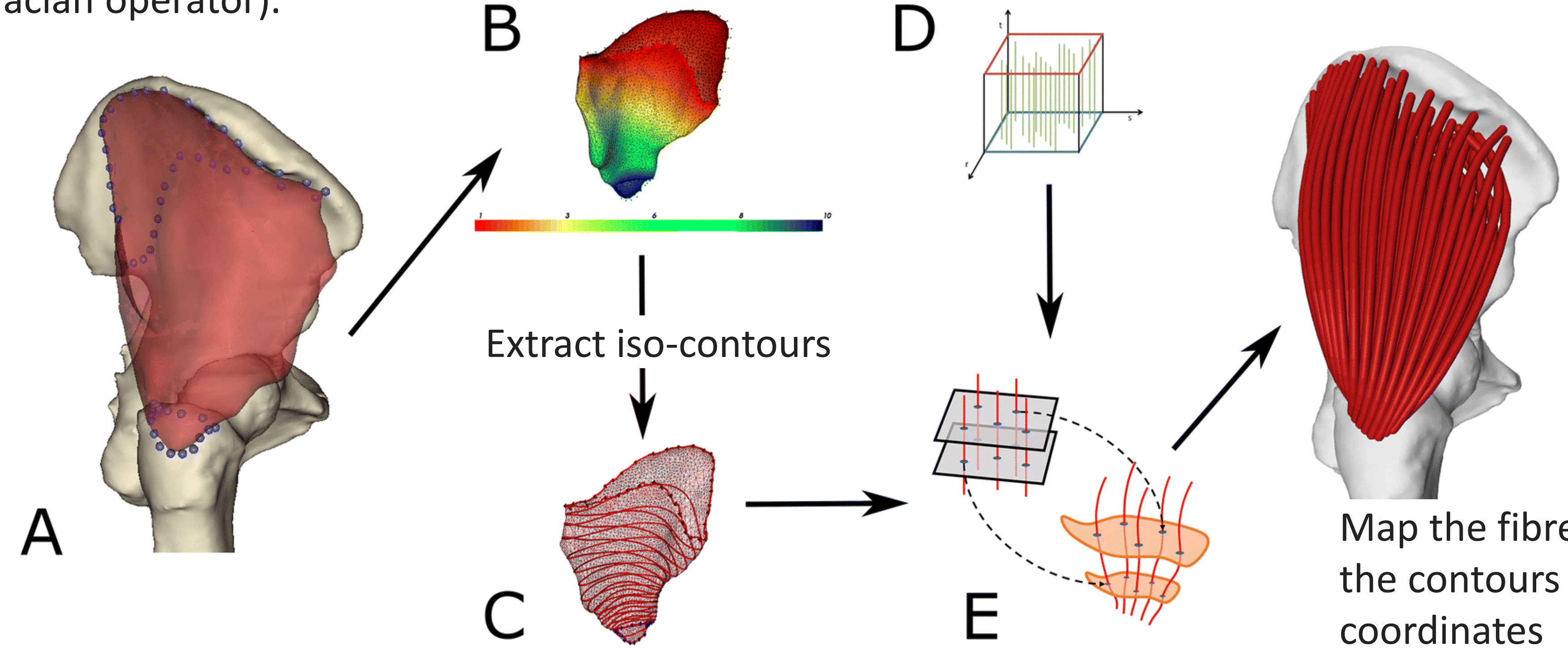
- **Challenge**: attachment areas show high inter-subject variability
- We could create a statistical atlas

Decompose muscles into fibres

Kohout, J., & Kukačka, M. (2014). Real-Time modelling of fibrous muscle. *Computer Graphics Forum*, *33*(8), 1–15. https://doi.org/10.1111/cgf.12354

Remove the attachment areas from the muscle mesh and compute a scalar field smoothly interpolating values between both attachment areas (using the Laplacian operator).

Slice the muscle architecture template



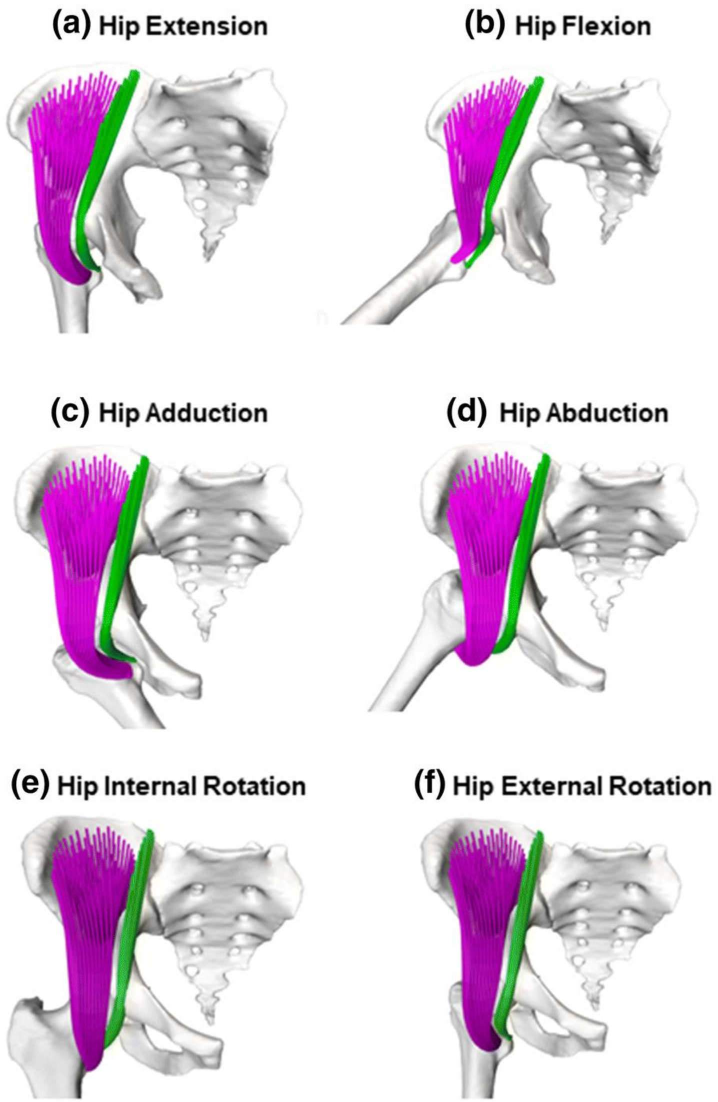
Map the fibre points from the slices to the contours using mean value coordinates

Deform muscles

- We may decompose the muscle into as many fibres as required
- Each fibre is a polyline of a user-specified number of segments
- With the number of segments being one, we can directly use the classical approaches to update their geometry in reaction to the movement of bones
- **Challenge**: How do we update the geometry of fine fibres?

Deform muscles

- During the simulation, each point of the fibre is subject to non-linearly weighted transformations of the bones connected by the fibre
- Weights determine how quickly the influence of an attachment bone diminishes along the fibre
  - $w_{i,1} = f\left(\frac{i-1}{n-1}\right), w_{i,2} = 1 - w_{i,1}$
  - $f(t) = \alpha \cdot (t^2 - t) - t + 1$
  - α is the muscle specific parameter



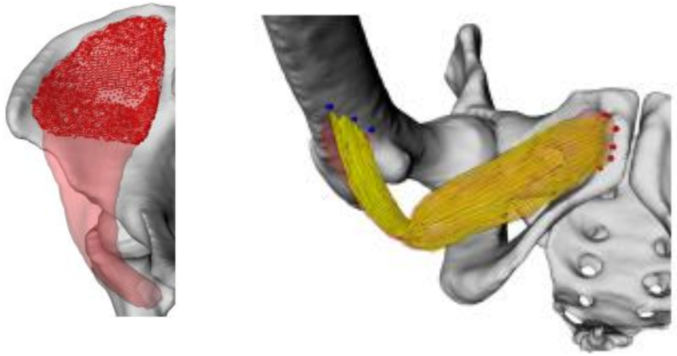
Modenese, L., & Kohout, J. (2020). Automated generation of Three-Dimensional complex muscle geometries for use in personalised musculoskeletal models. *Annals of Biomedical Engineering*, *48*(6), 1793–1804. https://doi.org/10.1007/s10439-020-02490-4

Deform muscles

- **Challenge**: Fibres are free to intertwin and may penetrate bones
  - Note: this disadvantage is common to practically all classical models
- Basic idea:
  - deform the surface model of the muscle while preserving its volume and avoiding muscle-bone and muscle-muscle penetrations
  - fibres geometry can be quickly restored using mean value coordinates
    - it is the same algorithm as in the muscle decomposition

Deform muscles

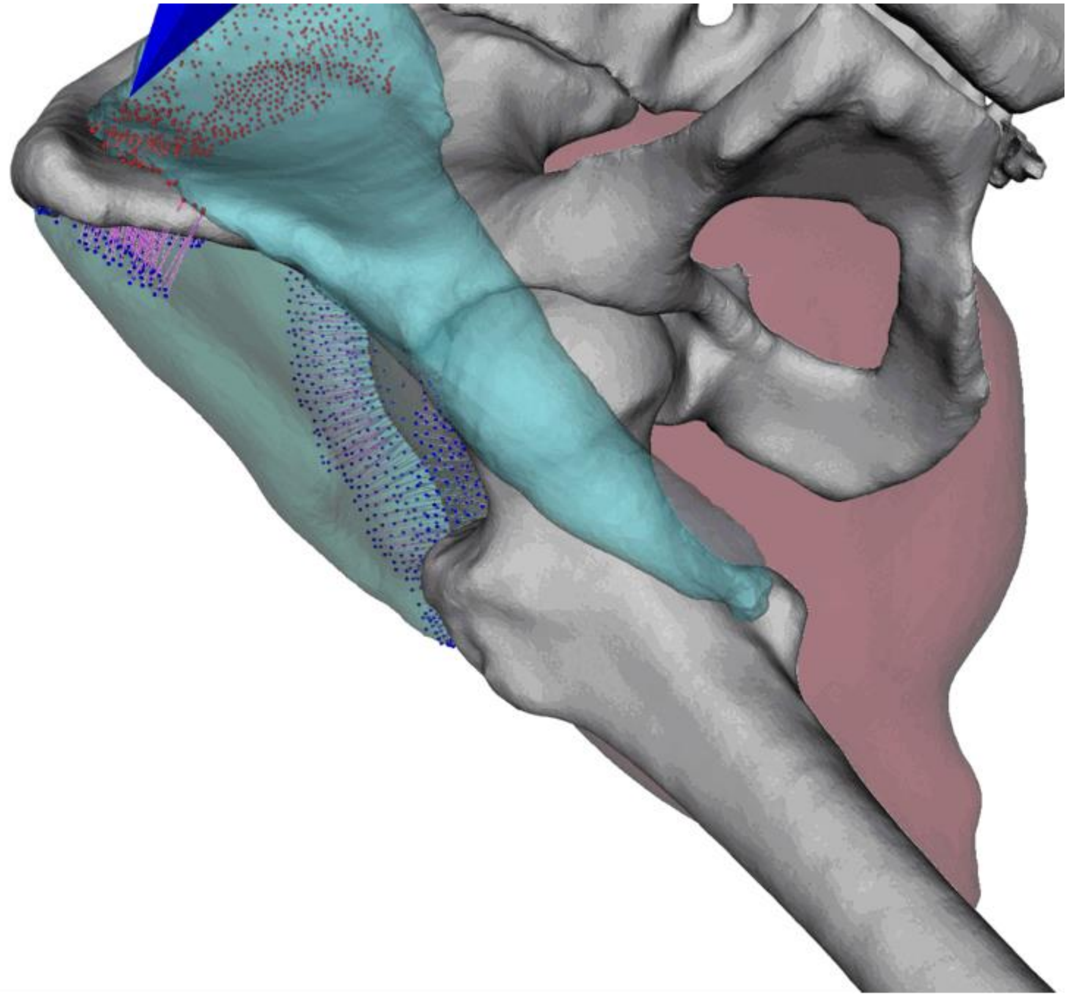
- Muscle vertices in proximity to the attachment areas are bound to the bones and move with them
- Position Based Dynamics (Mueller, 2007) (PBD)iteratively updates the position of all other vertices to restore the original:
  - lengths of the edges of the triangles representing the surface of the muscle
  - dihedral angles between pairs of triangles
  - volume of the muscle
    - hard constraint



Kohout, J., & Červenka, M. (2021). Muscle deformation using position based dynamics. In *Communications in computer and information science* (pp. 486–509). https://doi.org/10.1007/978-3-030-72379-8_24

Deform muscles

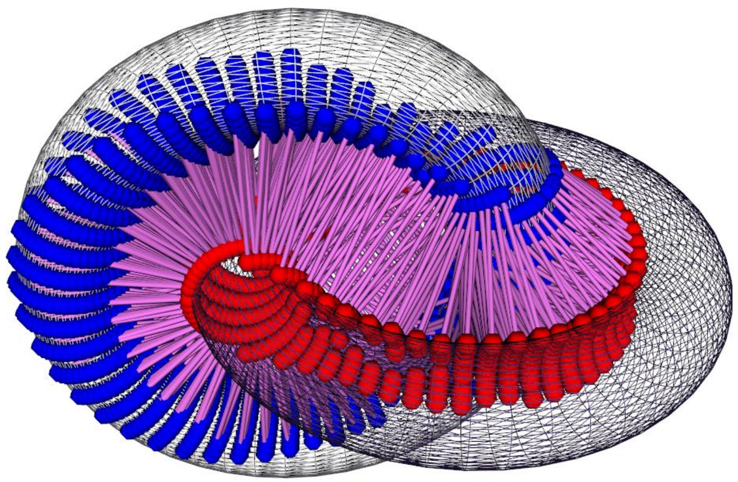
- A signed distance field (implemented in Discregrid) used to detect (and correct) collisions of the muscles and the bones during PBD iterations
- Disadvantage:
  - Unrealistic behaviour in some cases
    - Muscles are not sufficiently stiff
    - Muscles are treated as soft objects

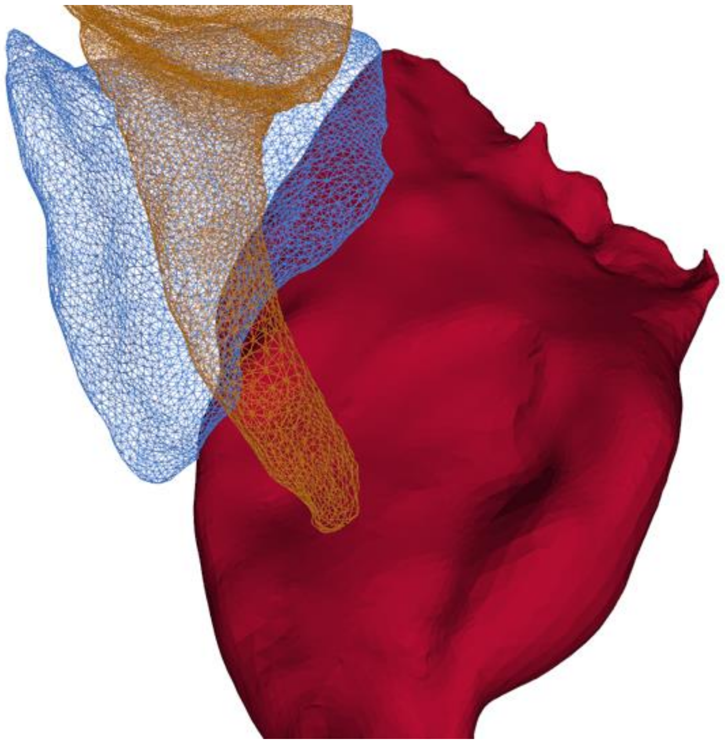


Havlicek, O., Cervenka, M., & Kohout, J. (2022). ***Collision detection and response approaches for computer muscle modelling*****. https://doi.org/10.1109/informatics57926.2022.10083500**

Deform muscles

- Extended PBD (XPBD, Macklin 2016) used to avoid sensitivity of PBD
- Added concept of virtual edges automatically created between adjacent muscles to avoid muscle-muscle penetration

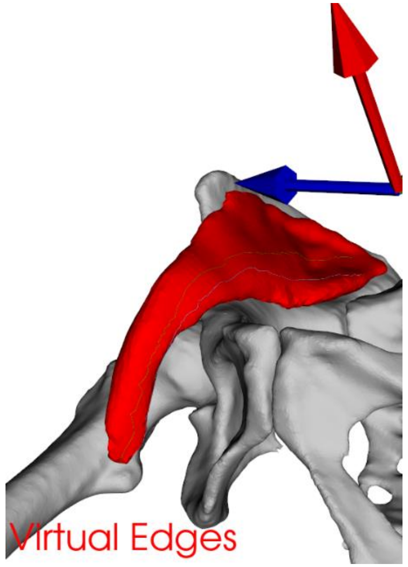




Havlicek, O. Muscle interaction in the context of muscle deformation modelling by a Position Based Dynamics method. Master thesis. 2024

Deform muscles

- Virtual edges with time-varying length parameters used to allow active contraction of the muscle
  - length parameters estimated from the knowledge of activation levels



1

1

Havlicek, O. Muscle interaction in the context of muscle deformation modelling by a Position Based Dynamics method. Master thesis. 2024

Conclusions

- In the last decade, we have developed an approach to musculoskeletal modelling that may outperform classical models
  - It has stirred the biomechanical community
- Work is still far from being perfect
  - Full workflow publicly available is required
    - It needs time to polish it and publish everything

Thank you for your attention

Josef Kohout / besoft@kiv.zcu.cz