Physics-Based Soft-Tissue Modelling and Simulation

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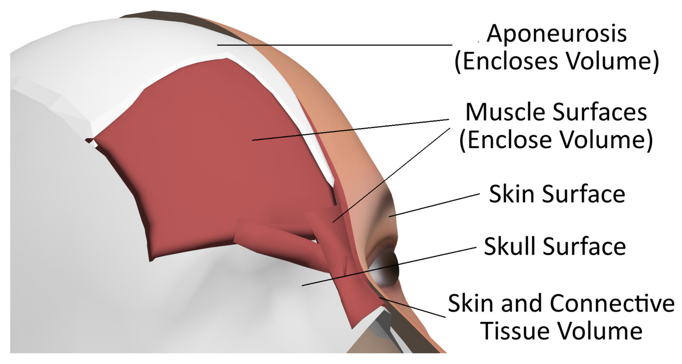
Introduction

- Soft-tissue modelling and simulation is a challenging area of computational biomechanics.
- **Hypothesis:** A physics-based approach enables more realistic and accurate simulations to be created, and automatic simulation of complex behaviour.
- **Aim:** Simulate soft tissue, including skin wrinkles, using a biomechanical model.



Contribution

- We have developed a physics-based approach for efficiently simulating both large areas of soft tissue, and detail such as skin layers (necessary to produce wrinkles), focussing on the forehead. This includes:
  - Automatic creation of simulation-ready non-conforming voxel-based FE models with bound surface meshes
  - Simulation using a GPU-based non-linear total Lagrangian explicit dynamic finite element (TLED FE) solver

Related Work

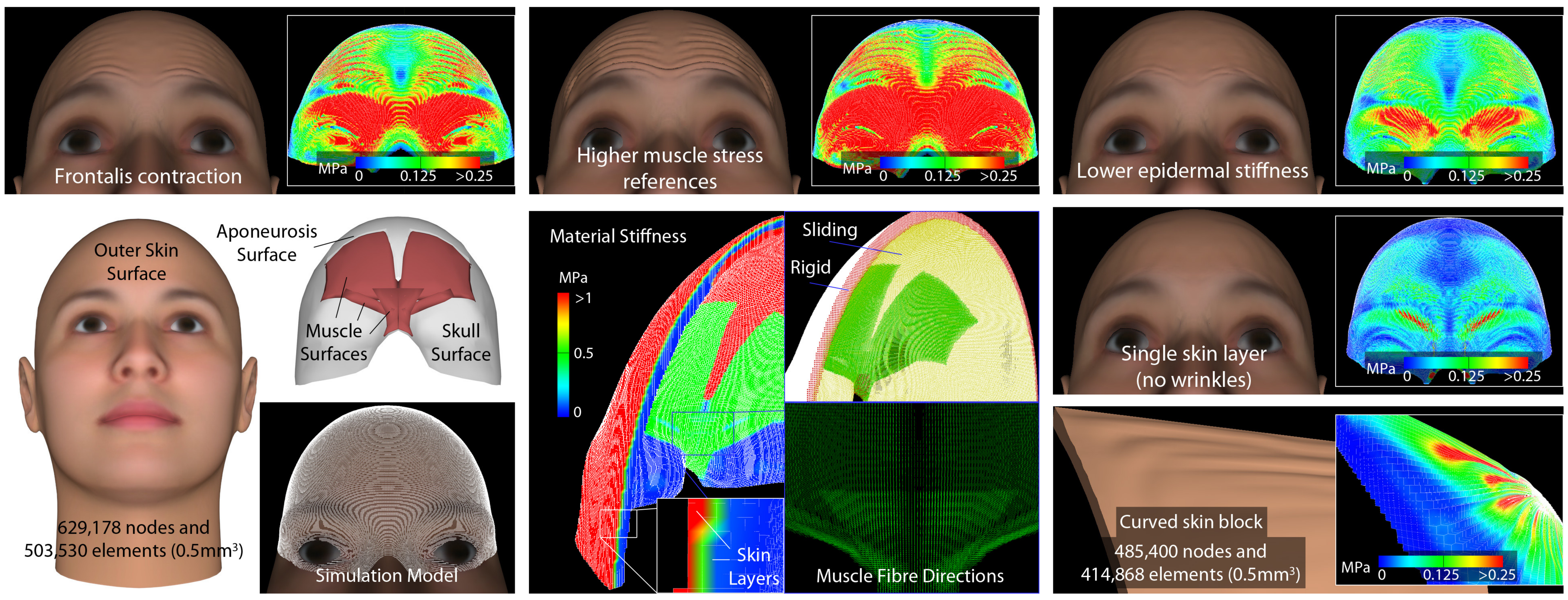
- Physics-based soft-tissue systems often focus on either:
  - Producing realistic-looking animations for computer graphics applications using the mass spring (MS) method [1]
  - Simulating detailed models of small areas with high accuracy to study soft-tissue behaviour [2], or surgical simulations [3] using the finite element (FE) method
- Simulation models can conform to a surface mesh [4], or a non-conforming model (e.g. a voxel representation) can be used [5] for efficient production of stable, realistic-looking animations.
- Muscles can be modelled as vectors or volumes. For contraction, a Hill-type model can be used with fibre field directions [6], and such models may be biologically inspired [7].
- FE facial models have been used to simulate gross facial movement [4, 7], and multi-layered FE models have been developed for accurate soft-tissue and skin wrinkle simulation [2, 8], although these focus on small areas of soft tissue.
  - Large speed increases can be achieved using the GPU [9].
- Our approach simulates fine detail, such as skin wrinkles, on large, complex areas like the forehead.

Results

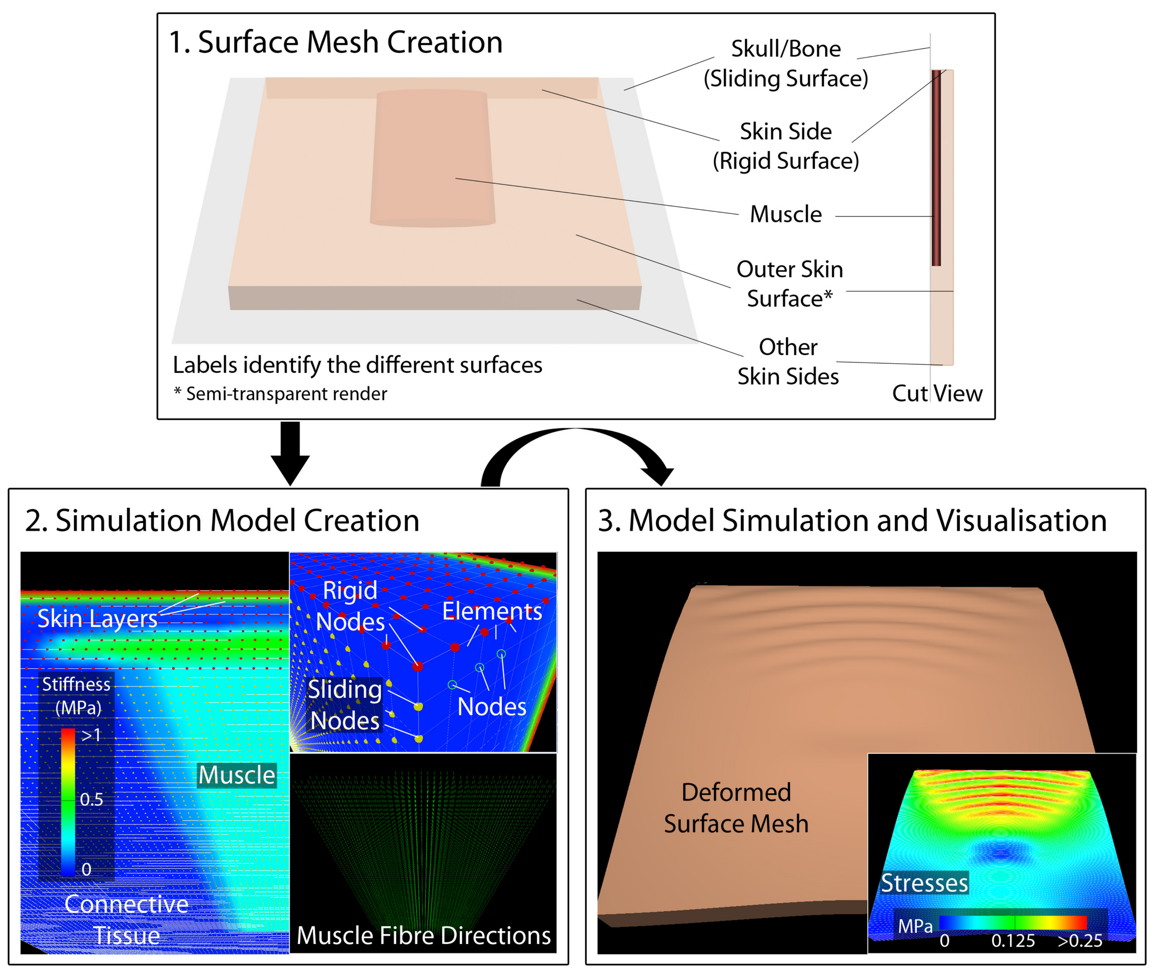
- Manually created forehead model with anatomical structure and neo-Hookean material properties.

Layer	Young's Modulus (MPa)	Depth (mm)
Stratum Corneum	48	0.02
Dermis	0.0814	1.8
Hypodermis	0.034	Remains
Muscle	0.5	~1
Tendon	24	~1

  - Each layer had a mass density of 11,000 kg/m^3 (with mass scaling), and a Poisson ratio of 0.49.
  - High epidermal stiffness produces desired average element stiffness when combined with the dermis.
- Muscles had 5MPa stress references, and were contracted linearly to 75%, with time scaling.
- 6.83ms to compute a 5μs timestep (NVIDIA GTX 680).



Simulation Process Overview



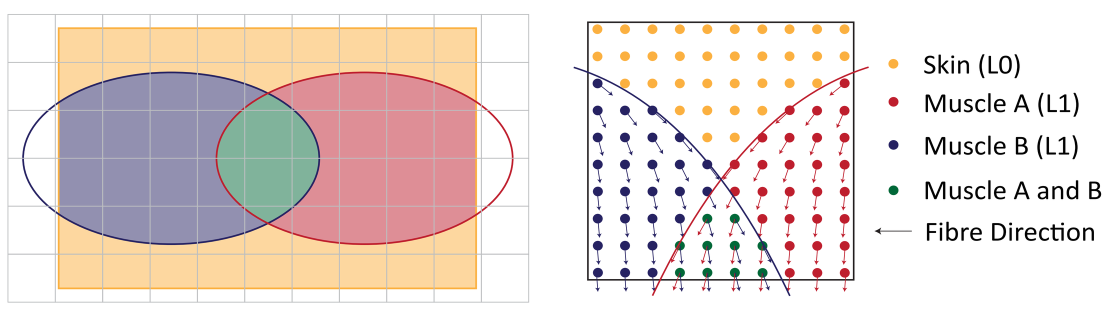
- We use non-conforming hexahedral (voxel-based) models due to model creation, performance and stability advantages [5].
- Further details of our model creation system (stage 2) and simulation system (stage 3) have been previously presented [10, 11, 12].

1. Surface Mesh Creation

- The surface mesh can be created using any 3D modelling tool.
- It can contain various surfaces, including internal surfaces.
- Volumes are user-defined as closed collections of surfaces.
  - A facial mesh may have a skin volume (between the skin and skull surfaces), and a volume for each muscle.
- Properties (such as material and muscle properties) are associated with each volume.
- Volume overlap represents the blend between materials, such as the blend between muscle fibres.

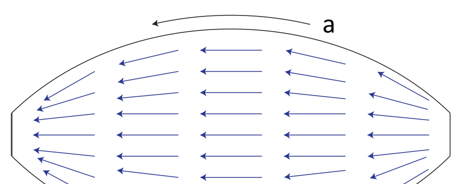
2. Automatic Simulation Model Creation

- Surface mesh volumes are voxelised, and voxel element material and muscle properties are calculated based on the proportions of overlap between the voxels and mesh volumes.
  - Voxelisation uses a sampling procedure.

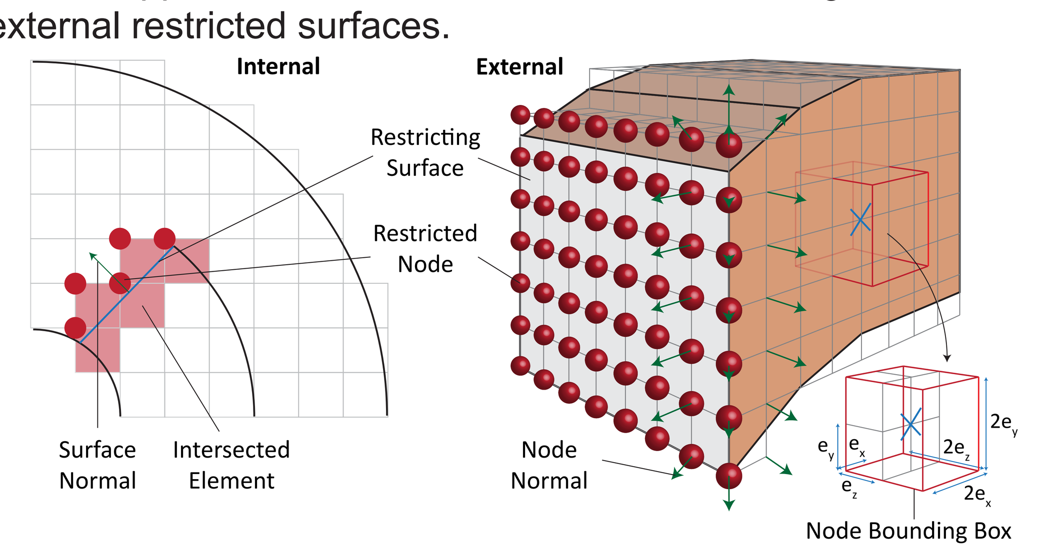


  - Constant-thickness skin layers are created, the boundaries of which may overlap. As the epidermis is too thin for sampling, epidermal properties are combined with all outer skin elements.
- Gradients of NURBS volume muscle approximations are used as muscle fibre fields.

$$d(\boldsymbol{x}) = \frac{\dfrac{\partial V\left(V^{-1}(\boldsymbol{x})\right)}{\partial a}}{\left\|\dfrac{\partial V\left(V^{-1}(\boldsymbol{x})\right)}{\partial a}\right\|}$$



  - NURBS volumes are created by shrinking NURBS surfaces.
- Restricted nodes, with rigid (fixed) or sliding constraints, are identified to approximate a collection of non-conforming internal and external restricted surfaces.



- Surface mesh vertices are bound to elements, and updated during simulations using trilinear interpolation and extrapolation.

3. Model Simulation

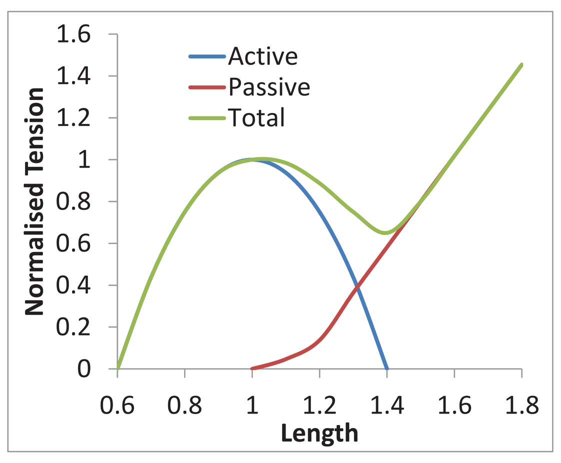
- We have developed a GPU-based non-linear TLED FE solver that is optimised for simulation of voxel-based models.
  - Inherently parallel, and highly suitable for large soft-tissue deformations with a small but efficient timestep.
  - The elements are reduced-integration 8-node hexahedra (no volume locking when simulating incompressible soft tissue).
- Uncoupled equation of motion:

$$\boldsymbol{M}\,{}^{t}\ddot{\boldsymbol{u}} + \boldsymbol{C}\,{}^{t}\dot{\boldsymbol{u}} + k({}^{t}\boldsymbol{u})\,{}^{t}\boldsymbol{u} = {}^{t}\boldsymbol{r}$$

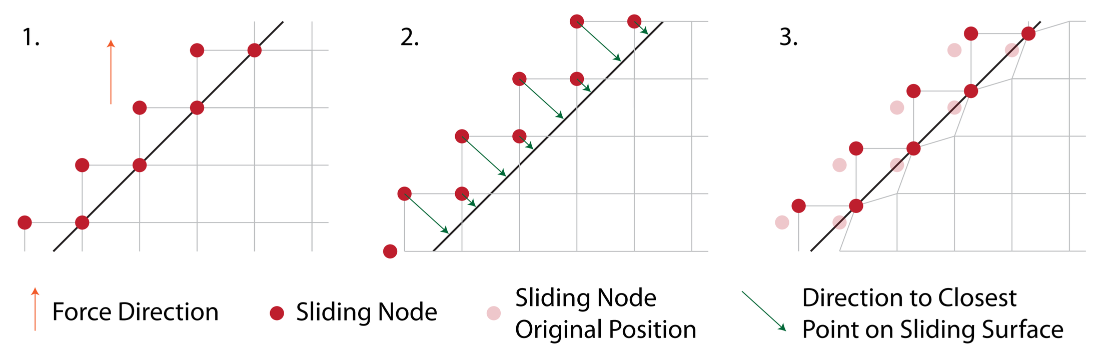
- Element nodal force contributions:

$${}^{t}f = k({}^{t}\boldsymbol{u})\,{}^{t}\boldsymbol{u} = \int_{{}^{0}V} {}^{t}_{0}\boldsymbol{B}_{L}^{T}\,{}^{t}_{0}\hat{\boldsymbol{s}}\, d\,{}^{0}V$$

- Stiffness-based hourglass control is used to surpress zero-energy modes that occur with under-integrated elements.
- Active and transversely isotropic passive stresses are generated in the fibre direction for each muscle overlapping an element.
  - Weighted by element-muscle overlap.
  - Follow muscle tension-length properties.

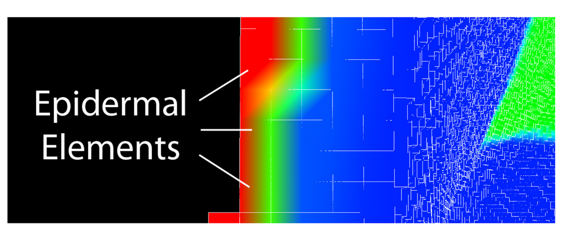


- Rigid nodes have zero displacement, for example, to model muscle attachments.
- Sliding nodes remain fixed from a non-conforming surface, for example, to model the sliding of superficial facial soft-tissue layers over the stiff deep layers.
  - Facilitated using GPU-based semi-brute-force broad-phase collision detection.



Conclusion

- Our physics-based soft-tissue simulation approach includes:
  - Creation of simulation-ready non-conforming hexahedral FE models with bound surface meshes
  - Model simulation using a GPU-based TLED FE solver
- Can simulate fine details like skin wrinkles.
- Improvements and future work include:
  - Using shell elements to more accurately model the thin epidermis.
  - Simulating different aged skin, and using more accurate material models.



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