Soft tissue simulation

- Feasibility and practicality of a novel teaching aid for microvascular anastomosis simulation training in neurosurgery generated by 3D printing
- Revisiting Härtel's technique for percutaneous transoval glycerol injection
- Application of Augmented Reality Navigation in Craniofacial Surgery for Fibrous Dysplasia
- Evaluating the impact of a hand-crafted 3D-Printed head Model and virtual reality in skull base surgery training
- Learning soft tissue deformation from incremental simulations
- Modeling, experiment, and validation of a piglet head
- Design, fabrication, and testing of a new soft-pouch robot with 6 degrees of freedom to expand the reach of open and endonasal skull base approaches
- Intraoperative interaction modeling between surgical instruments and soft tissues in neurosurgery based on energy functions

Soft tissue simulation refers to the use of computational models to replicate the physical behavior of soft tissues, such as the brain, spinal cord, and surrounding structures, in virtual environments. This technology is pivotal in neurosurgery for training, planning, and guiding complex procedures.

A physical model of soft tissue that provides realistic and real-time haptic and visual feedback is crucial for neurosurgical procedures.

Key Goals

1. **Realism:**

   1. Accurately mimic the mechanical and physical properties of soft tissues under various conditions.
   2. Provide realistic deformation, cutting, and interaction dynamics during surgical tasks.

2. **Safety:**

   1. Enable surgeons to practice and refine techniques without risks to patients.
   2. Facilitate preoperative planning to anticipate challenges and minimize complications.

3. **Real-Time Performance:**

   1. Deliver immediate feedback during simulations to support training and intraoperative applications.

Components of Soft Tissue Simulation

1. **Biomechanical Modeling:**

   1. Soft tissues exhibit nonlinear, viscoelastic properties that are influenced by forces such as compression, tension, and shear.
   2. Common modeling approaches:

1. **Finite Element Models (FEM):** Highly accurate but computationally intensive, ideal for preoperative planning.
2. **Mass-Spring Models:** Simplified and faster, often used in real-time simulations.
3. **Mesh-Free Methods:** Handle large deformations and topological changes, such as cutting and tearing.

2. **Tissue Properties:**

1. Mechanical properties like elasticity, viscosity, and density are critical for realistic simulations.
2. Parameters are often derived from imaging techniques like elastography or direct measurements.

3. **Tissue Interaction Dynamics:**

1. Cutting, retraction, and probing interactions with surgical instruments must be modeled precisely.
2. Incorporates factors like friction, adhesion, and tool pressure.

4. **Energy Functions:**

1. Governs tissue deformation by balancing elastic potential, volume preservation, and frictional energy dissipation.

5. **Visualization:**

1. Advanced rendering techniques provide detailed and realistic visual feedback of tissue deformation and tool interactions.

6. **Haptic Feedback:**

1. Simulated tactile responses mimic the physical sensations of interacting with soft tissues, enhancing training fidelity.

Applications of Soft Tissue Simulation

1. **Surgical Training:**

1. Provides a risk-free environment for practicing complex neurosurgical procedures.
2. Allows simulation of rare or high-stakes scenarios like tumor resection or aneurysm clipping.

2. **Preoperative Planning:**

1. Facilitates rehearsal of procedures using patient-specific anatomical models.
2. Aids in understanding tissue behavior and optimizing surgical approaches.

3. **Intraoperative Guidance:**

1. Real-time simulations integrated with imaging and navigation systems guide surgeons during procedures.
2. Adapts dynamically to tissue deformation and tool movements.

4. **Device Testing:**

1. Assists in the design and validation of new surgical instruments and robotic systems.

5. **Research and Development:**

   1. Enables the study of biomechanical properties of soft tissues under various conditions.
   2. Tests hypotheses about surgical techniques and their effects on tissue integrity.

Challenges in Soft Tissue Simulation

1. **Computational Complexity:**

   1. Realistic modeling of soft tissues requires high computational resources, particularly for real-time applications.

2. **Data Acquisition:**

   1. Obtaining accurate tissue property data is challenging, especially for patient-specific simulations.

3. **Model Validation:**

   1. Ensuring the simulation replicates real-world tissue behavior requires rigorous testing and validation.

4. **Integration with Surgical Workflows:**

   1. Simulations must seamlessly integrate with existing tools like navigation systems and microscopes.

Emerging Trends

1. **Patient-Specific Models:**

   1. Advances in imaging technologies like MRI and CT enable creation of personalized simulations tailored to individual anatomy.

2. **Machine Learning Integration:**

   1. AI algorithms predict tissue behavior and adapt simulations based on real-time data.

3. **Improved Biomechanical Models:**

   1. Development of hybrid models combining FEM with faster, more flexible methods for real-time use.

4. **Cloud-Based Simulations:**

   1. Cloud computing allows remote access to high-fidelity simulations, expanding accessibility.

5. **Virtual and Augmented Reality (VR/AR):**

1. Immersive environments enhance visualization and interaction with soft tissue models.

Prospective educational intervention studies

While cadaveric dissections remain the cornerstone of education in skull base surgery, they are associated with high costs, difficulty acquiring specimens, and a lack of pathology in anatomical samples.

A study of Mellal et al. evaluated the impact of a hand-crafted three-dimensional (3D)-printed head model and virtual reality (VR) in enhancing skull base surgery training.

Research question: How effective are 3D-printed models and VR in enhancing training in skull base surgery?

A two-day skull base training course was conducted with 12 neurosurgical trainees and 11 faculty members. The course used a 3D-printed head model, VR simulations, and cadaveric dissections. The 3D model included four tumors and was manually assembled to replicate tumor-modified neuroanatomy. Trainees performed surgical approaches, with pre- and post-course self-assessments to evaluate their knowledge and skills. Faculty provided feedback on the model's educational value and accuracy. All items were rated on a 5-point scale.

Trainees showed significant improvement in understanding spatial relationships and surgical steps, with scores increasing from 3.40 ± 0.70 to 4.50 ± 0.53 for both items. Faculty rated the educational value of the model with a score of 4.33 ± 0.82, and a score of 5.00 ± 0.00 for recommending the 3D-printed model to other residents. However, realism in soft tissue simulations received lower ratings.

Virtual reality and 3D-printed models enhance anatomical understanding and surgical training in skull base surgery. These tools offer a cost-effective, realistic, and accessible alternative to cadaveric training, though further refinement in soft tissue realism is needed [1)]

Computational and experimental modeling studies

Wang et al. investigates the interaction between neurosurgical instruments and soft brain tissue, proposing a soft tissue deformation simulation method based on the principle of energy minimization and constrained energy function. The model includes a permanent deformation energy function induced by friction and a volume preservation energy function to more accurately depict tissue response during procedures such as resection of convexity meningiomas and evacuation of intracerebral hematomas. Experimental results show that the proposed method meets the requirements of neurosurgical simulation [2)]

1)

Mellal A, González-López P, Giammattei L, George M, Starnoni D, Cossu G, Cornelius JF, Berhouma M, Messerer M, Daniel RT. Evaluating the impact of a hand-crafted 3D-Printed head Model and virtual reality in skull base surgery training. Brain Spine. 2024 Dec 12;5:104163. doi: 10.1016/j.bas.2024.104163. PMID: 39802866; PMCID: PMC11718289.

2)

Wang T, Wang J, Li Z, Ramík DM, Ji X, Moreno R, Zhang X, Ma C. Intraoperative interaction modeling between surgical instruments and soft tissues in neurosurgery based on energy functions. Comput Methods Biomech Biomed Engin. 2024 Nov 25:1-15. doi: 10.1080/10255842.2024.2431892. Epub ahead of print. PMID: 39587726.