Determining Deformable Model Parameters and Assessing the Haptic Rendering Fidelity

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Context – Surgical Simulation
Realism in Surgical Simulation

- Target: optimal training
- Required degree of realism?
- Realism vs. complexity
- Realism vs. cost
- Realism vs. training effect
Realism in Surgical Simulation

- Fidelity affected by several modules
- Necessity (and required fidelity) of haptic feedback still unclear
- Haptics main cause of high costs
Haptic Rendering Pipeline

- Tissue parameters
- Deformation model
- Collision detection
- Haptic coupling
- Hardware

Haptic rendering pipeline
Characteristics of Living Soft Tissue

- Non-homogeneity
- Tissue yield
- Anisotropy
- Conditioning
- Visco-elastic behavior
- Non-linear material
Data-Driven Parameter Estimation

- In-vivo measurements of parameters
- Assumption of non-linear, visco-elastic material
- Optimization via inverse calculations
- Differences in healthy and pathologic tissue
- Approval from ethics board needed

Tissue Aspiration Experiments
Analytical Parameter Derivation

- Obtain parameters from known model (e.g. FEM solution)
- Discretize object and determine numerical description
- Equate description and derive analytical solution
- Quasi-static Finite Element model for linear elasticity

\[ f = K_{FEM} u \]

- Linearized quasi-static mass-spring model

\[ f \cong f_0 + \frac{df_0}{dx} u = f_0 + K_{MSM} u \]

[Van Gelder 1998, Lloyd et al. 2007]
Analytical Parameter Derivation

- FE stiffness matrix (constant strain triangle)

\[
f = K_{FEM} u = \begin{bmatrix}
  K_{i,i} & K_{i,j} & K_{i,k} \\
  K_{j,i} & K_{j,j} & K_{j,k} \\
  K_{k,i} & K_{k,j} & K_{k,k}
\end{bmatrix} u
\]

\[
K_{i,k} = \frac{tE}{4A(1+\nu)(1-\nu)} \begin{bmatrix}
  \beta_i \beta_k + \gamma_i \gamma_k \frac{1-\nu}{2} & \beta_i \gamma_k + \beta_k \gamma_i \frac{1-\nu}{2} \\
  \beta_k \gamma_i + \beta_i \gamma_k \frac{1-\nu}{2} & \gamma_i \gamma_k + \beta_i \beta_k \frac{1-\nu}{2}
\end{bmatrix}
\]

\[
\beta_i = y_j - y_k \quad \beta_j = y_k - y_i \quad \beta_k = y_i - y_j
\]

\[
\gamma_i = x_j - x_k \quad \gamma_j = x_k - x_i \quad \gamma_k = x_i - x_j
\]
Analytical Parameter Derivation

- Matrix of triangular “element” of linearized MSM

\[
\mathbf{f} \simeq \mathbf{K}_{\text{MSM}} \mathbf{u} = \begin{bmatrix}
A_{i,j} + A_{i,k} & -A_{i,j} & -A_{i,k} \\
-A_{i,j} & A_{i,j} + A_{j,k} & -A_{j,k} \\
-A_{i,k} & -A_{j,k} & A_{i,k} + A_{j,k}
\end{bmatrix} \mathbf{u}
\]

\[
A_{i,k} = \frac{k_{i,k}}{(l_{i,k}^0)^2} \begin{bmatrix}
(x_i - x_k)^2 & (x_i - x_k)(y_i - y_k) \\
(x_i - x_k)(y_i - y_k) & (y_i - y_k)^2
\end{bmatrix}
\]
Analytical Parameter Derivation

- Equate matrices, simplify by transformation
- Exact solution for equilateral triangles
- Approximate solutions for other elements

\[ k_{i,k} = \sum_{e} E_t \frac{\sqrt{3}}{4} \]
Assessing the Haptic Rendering Fidelity

• Quantify effect of fidelity on user perception
• Determine relation between physical and perceptual dimensions
• Map via Multidimensional Scaling (MDS)
  — Investigates underlying dimensionality in stimuli set
  — Based on dissimilarity ratings
• Experiment: haptic interaction with linear elastic, homogenous objects

Multidimensional Scaling

• Steps
  — Obtain dissimilarity rating $\delta_{p,q}$ for all pairs $(p,q)$ of $n$ objects
  — Determine low-dimensional perceptual space
  — Represent objects in perceptual space

• Characteristics
  — Maintains inter-stimulus distances $d_{p,q}$ in perceptual space
  — Determines number of dimensions of variation perceived
  — Assigns weights to psychological dimensions
  — Labels of dimensions need to be provided
  — Invariant to rotation, translation, reflection
MDS Example

Stimuli

1 2 3 4

Input

Dissimilarities

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MDS

Perceptual space

Output

Size

Color

Stress

0.2

1D 2D 3D

Dimension weights

S1 S2

Relative weight

col. size

S1 S2
Assessment Study of Rendering Fidelity

- Comparison of real and virtual objects
- Varying levels of rendering fidelity
- Evaluation of complete pipeline (parameters, tissue model, hardware)
- Simplified tool-object interaction
- Subjective user similarity rating
Real Deformable Objects – Stimuli 1-7

- Silicone cylinders (400g)
- 80mm height × 80mm diameter
- ECOFLEX 0030/40, silicone thinner
- Linear elastic behaviour close to soft tissue (in the linear range)
- 16-84kPa Young's modulus
- Poisson ratio 0.499
Virtual Deformable Objects – Stimuli 8-14

- Mass-spring-damper model
- Linear springs
- Volume preserving forces
- Point-based proxy
- Separate threads for haptics & deformation
- Varying feedback fidelity due to filtering
Virtual Objects Parameter Setting

- **Object mesh**: 300 nodes, 1656 edges, 1156 tetrahedra
- **Mass (400g)**

\[
\int_{\text{Body}} u^j_x u^k_y u^l_z \rho (\ddot{u}) d\ddot{u} = \sum_{i=1}^{n} u^j_{x_i} u^k_{y_i} u^l_{z_i} m_i \quad j + k + l \leq 2
\]

\[
\min \left( \sum_{i} (m_i - c \sum_{v_i \in T} \text{Volume}(T)) ^2 \right)
\]

- **Elasticity (16-84kPa)**

\[
k_e = \frac{E \sum_{e \in T} \text{Volume}(T)}{\text{Length}(e)^2}
\]

- **Time step**

\[
\Delta t = \sqrt{\frac{\text{mass}}{n \pi^2 k_{\text{max}}}}
\]

- **Proxy spring stiffness, damping**

Force Response During Interaction

**Force response of silicone samples**

- **Stiffness**
  - Real: 16, 23, 32, 37, 44, 69, 84
  - Virtual: 16, 21, 29, 34, 38, 55, 72

**Force response of virtual samples**
Experimental Setup

- PHANTom haptic device
- Flat indenter (8mm)
- Movement limited to 1D
- 25mm max indentation depth
- Objects hidden
- No visual feedback
- Participants wore earphones
Experimental Setup

- 10 participants, 5 blocks (525 trials p.p.)
- Comparison of object indentation pairs
- Virtual objects with varying fidelity
- Indentation depth and velocity limited
- Rate object similarity (1=low to 7=high)
- Similarity scale set during training phase
- Questionnaire filled after the experiment
Dissimilarity Data

Higher-fidelity condition

Lower-fidelity condition

MSE

0.59

0.55
MDS Results

Higher-fidelity condition

Lower-fidelity condition

real objects
higher-fidelity virtual objects
lower-fidelity virtual objects

Dimensionality of MDS Solution

Stress

1st Perceptual Dimension: Stiffness

2nd Perceptual Dimension

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Debriefing Questionnaires

• All but one assumed all tested objects being real
• One assumed all objects as virtual
• Nobody reported rendering fidelity or stability
• Majority of similarity categories related to stiffness
  — Foam, rubber, sponge, spring
  — Material property (soft, medium, hard)
• Other reported properties
  — “Hollowness” of objects
  — Objects with rigid shell and soft interior (balls, balloons, etc.)
  — Dynamic properties (bounciness, etc.)
Problems Due to Device Limitations

Stimulus 8

Stimulus 14
Conclusion

- Haptics pipeline in surgical simulation
- Quantification of perceptual dimensions
- Discrimination difficult between real and virtual objects
- Fidelity conditions recovered by MDS
- Problems due to device capabilities
- Limited dynamics of virtual objects
- Restricted interaction


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http://www.co-me.ch

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