Immersive Medical VR Training Simulators with Haptic Feedback

Maximilian Kaluschke
Challenges in Medicine

- Increased life expectancy
- Demographic shift
- Increased prevalence of mobility-related diseases
- Surgeon’s experience critical
  - Early, frequent practice
- Teaching difficulties
Challenges in Medical Training

- Orthopedic surgeries
  - Navigation by feeling, limited sight
  - Large forces

- Dental surgeries
  - Psycho-motor challenges
  - Precise bi-manual manipulation
  - Mirrored navigation
Traditional Medical Training

• Practice after students learn steps of procedures
• Practical training starts on physical dummies
  • Limited realism & high cost
• Donor organs when possible; realistic and safe
  • Low availability / high cost, no repeatability
• In practice, students assist during live procedures early
• VR simulators as complementary training
Potential of VR Simulators

- Repeatable, safe lessons
  - Low operational cost
  - Improve training quality
- Automated feedback
  - Reduce work for instructors
  - Objective feedback
VR Simulators State of the Art

- VR-only simulators
  - Logishetty et al. 2020
  - Rahman et al. 2024
- Haptic VR simulators
  - Bartlett et al. 2020
- Commercial hip surgery simulators
  - Fundamental Surgery, 2019
VR Simulators State of the Art

- Research gaps

1. High-force haptic feedback
2. Stepless haptic material removal
3. Efficacy of HMD-based VR haptic simulators
Simulator as a System

Haptics
- Read Haptic Device Pose
- Render Virtual Coupling Forces
- 1000 Hz

Physics
- Kinematic Update of Haptic Tool
- Integrate Dynamics of Graphic Tool
- Continuous Collision Detection
- Contact Detection
- Contact Resolution
- Surface Estimation
- Material Removal
- Velocity Correction
- 1000–3000 Hz

Game Engine(s)
- Visuals
  - Signed Distance Field
  - Bilateral Smoothing
  - Marching Cubes
  - 10 Hz
Simulator as a System

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1000-3000 Hz

10 Hz
Simulator as a System

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1000 Hz

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    - Contact Resolution
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1000–3000 Hz

**Game Engine(s)**

10 Hz

**Visuals**
- Signed Distance Field
- Bilateral Smoothing
- Marching Cubes

---

**Navigation**
- Introduction
- Collision
- Contact
- Material
- Haptics
- DentalSim
- HIPS
- Conclusions
Simulation: Physics

Pop through
Simulation: Physics

Incorrect contacts
Continuous Collision Detection
Continuous Collision Detection
CCD Optimization

- CCD: first contact of swept sphere vs. spheres
CCD Optimization

- CCD: first contact of swept sphere vs. spheres
- Spheres simplify translational CCD to ray vs spheres
CCD Optimization

- CCD: first contact of swept sphere vs. spheres
- Spheres simplify translational CCD to ray vs spheres

\[ t \approx 0.15 \text{ ms} \]

100k vs 2k spheres
Continuous Collision Detection

Haptics

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Physics

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Game Engine(s)

- Visuals
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Haptic Device(s)

1000 Hz

1000–3000 Hz

10 Hz
Contact Detection

Haptics
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Game Engine(s)

Visuals
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Haptic Device(s)

1000 Hz

1000–3000 Hz

10 Hz
Multiple Contacts without Overlap
Multiple Contacts without Overlap

~ 0.21 ms
100k vs 2k spheres
Contact Resolution

- Directly enforced
  - Constraint-based
  - Slow running time
- Indirectly enforced
  - Impulse-based
  - Position-based
  - Penalty-based
  - Fast running time
Haptic Rendering of Large Forces

- Abstracted three task from hip reaming
  - Worst case: steel on steel
- Rendering methods: penalty, impulse, rigid-body, constraint
Haptic Rendering of Large Forces

Perceived Realism of Haptic Rendering Methods in Both Studies

<table>
<thead>
<tr>
<th>Task 1 (contact)</th>
<th>Task 2 (rotation)</th>
<th>Task 3 (push)</th>
</tr>
</thead>
<tbody>
<tr>
<td>penalty</td>
<td>penalty</td>
<td>penalty</td>
</tr>
<tr>
<td>constraint</td>
<td>constraint</td>
<td>constraint</td>
</tr>
<tr>
<td>impulse</td>
<td>impulse</td>
<td>impulse</td>
</tr>
<tr>
<td>rigid body</td>
<td>rigid body</td>
<td>rigid body</td>
</tr>
</tbody>
</table>

Perceived Realism in Percentage

Original vs Replication

Introduction  Collision  Contact  Material  Haptics  DentalSim  HIPS  Conclusions
Hybrid Contact Resolution Approach

- Colliding contacts have velocity *constraints*
- Iteratively apply partial *impulses* with friction
- Resting contacts resolved using *penalty* force

\[
\vec{j}_i^n = \frac{1}{N} \vec{n}(c_i)^T (I^{-1} (\vec{r}'(c_i) \times \vec{n}(c_i)) \times \vec{r}(c_i)) \quad - (1 + e)\vec{p}(c_i)
\]

\[
\vec{f}(c_i) = V(c_i) \vec{n}(c_i) k_c
\]
Contact Resolution Approach
Simulation: Contact Resolution

Haptics
- Read Haptic Device Pose
- Render Virtual Coupling Forces
- 1000 Hz

Physics
- Kinematic Update of Haptic Tool
- Integrate Dynamics of Graphic Tool
- Continuous Collision Detection
- Contact Detection
- Contact Resolution
- Surface Estimation
- Material Removal
- Velocity Correction
- 1000–3000 Hz

Game Engine(s)
- Visuals
  - Signed Distance Field
  - Bilateral Smoothing
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  - 10 Hz

Haptic Device(s)

Introduction  Collision  Contact  Material  Haptics  DentalSim  HIPS  Conclusions
Simulation: Surface Estimation & Materials

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Haptic Device(s)
Material Removal

- Modulate tool feed rate based on following:
  1. Applied pressure by the user
  2. Cutting contact area
  3. Local material density (tooth layers, cortical bone)

- Cutting model
  - Define feed rates $r_d^{\text{ref}}$, $r_d^{\text{max}}$ per tool (for reference and max. pressure)
  - Modulate $r_d$ by local pressure: $|f_s + \tau_s \times \vec{r}_i|$
  - Modulate $r_d$ by global contact volume (density scaled), inversely
Material Removal
Material Removal (Cutting Direction)
Material Removal (Cutting Direction)

- Modulate *per contact* by angle of normal & drill direction
Stepless Material Removal

Introduction  Collision  Contact  Material  Haptics  DentalSim  HIPS  Conclusions
Material Removal: What About Friction?

Introduction  Collision  Contact  Material  Haptics  DentalSim  HIPS  Conclusions
Material Removal: What About Friction?

- Drilling friction
  - Increase point velocity during tangential impulse solve
Material Removal: What About Friction?

- Drilling friction
  - Increase point velocity during tangential impulse solve
Tool Sounds

- Increase immersion and realism of drilling
- Drilling tools have a distinct sound signature
- Frequency response modulation based on
  1. Motor rotation speed
  2. Cutting resistance
Tool Sounds
**Simulation: Visualization**

**Haptics**
- Read Haptic Device Pose
- Render Virtual Coupling Forces
- 1000 Hz

**Physics**
- Kinematic Update of Haptic Tool
- Integrate Dynamics of Graphic Tool
- Continuous Collision Detection
- Contact Detection
- Contact Resolution
- Surface Estimation
- Material Removal
- Velocity Correction
- 1000–3000 Hz

**Game Engine(s)**
- Visuals
  - Signed Distance Field
  - Bilateral Smoothing
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  - 10 Hz

**Haptic Device(s)**
Visualization Pipeline

- Precomputed: mesh → spheres
- Maintain dynamic mesh at runtime
  - Spheres → mesh (reverse)
- Interactive rates
- Visual quality & color
Visualization Pipeline

**Haptics**
- Read Haptic Device Pose
- Render Virtual Coupling Forces
- Haptic Device(s)

**Physics**
- Kinematic Update of Haptic Tool
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- 1000–3000 Hz

**Game Engine(s)**
- Visuals
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- 10 Hz

**1000 Hz**
Visualization Pipeline

**Haptics**
- Read Haptic Device Pose
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**Physics**
- Kinematic Update of Haptic Tool
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**Game Engine(s)**

**Visuals**
- Signed Distance Field
- Bilateral Smoothing
- Marching Cubes

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**Haptic Device(s)**

**Timeline**
- 1000 Hz
- 1000–3000 Hz
- 10 Hz

**Sections**
- Introduction
- Collision
- Contact
- Material
- Haptics
- DentalSim
- HIPS
- Conclusions
Visualization (Signed Distance Field)
Visualization (Signed Distance Field)
Visualization (Signed Distance Field)
Visualization (Signed Distance Field)
Visualization (Signed Distance Field)
Simulation: Signed Distance Field

Haptics
- Read Haptic Device Pose
- Render Virtual Coupling Forces
  1000 Hz

Physics
- Kinematic Update of Haptic Tool
- Integrate Dynamics of Graphic Tool
- Continuous Collision Detection
- Contact Detection
- Contact Resolution
- Surface Estimation
- Material Removal
- Velocity Correction
  1000–3000 Hz

Game Engine(s)
- Visuals
  - Signed Distance Field
  - Bilateral Smoothing
  - Marching Cubes
  10 Hz

Haptic Device(s)
Simulation: Bilateral Smoothing

Haptics
- Read Haptic Device Pose
- Render Virtual Coupling Forces

Physics
- Kinematic Update of Haptic Tool
- Integrate Dynamics of Graphic Tool
- Continuous Collision Detection
- Contact Detection
- Contact Resolution
- Surface Estimation
- Material Removal
- Velocity Correction

Game Engine(s)
- Visuals
  - Signed Distance Field
  - Bilateral Smoothing
  - Marching Cubes

1000 Hz
1000–3000 Hz
10 Hz

Haptic Device(s)
Visualization (Bilateral Smoothing)

No smoothing, Triangle normals

Smoothing, Triangle normals

Smoothing, Sphere normals

Introduction  Collision  Contact  Material  Haptics  DentalSim  HIPS  Conclusions
Simulation: Bilateral Smoothing

Haptics
- Read Haptic Device Pose
  - Render Virtual Coupling Forces
  - 1000 Hz

Physics
- Kinematic Update of Haptic Tool
- Integrate Dynamics of Graphic Tool
- Continuous Collision Detection
  - Contact Detection
  - Contact Resolution
  - Surface Estimation
  - Material Removal
  - Velocity Correction
  - 1000–3000 Hz

Game Engine(s)
- OpenGL

Visuals
- Signed Distance Field
  - Bilateral Smoothing
  - Marching Cubes
  - 10 Hz
Simulation: Marching Cubes

Haptics
- Read Haptic Device Pose
- Render Virtual Coupling Forces

Physics
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Game Engine(s)
- Visuals
  - Signed Distance Field
  - Bilateral Smoothing
  - Marching Cubes

Haptic Device(s)

1000 Hz
1000–3000 Hz
10 Hz
Visualization (Marching Cubes)

- Parallel MC on GPU
  - Extended by LERP’d sphere normal & colors
- Coarser grid to store triangles
- Reduce data by vertex pooling
  - Including normal & colors
Simulation: Marching Cubes

Haptics

- Read Haptic Device Pose
- Render Virtual Coupling Forces

Physics

- Kinematic Update of Haptic Tool
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Game Engine(s)

- OpenGL

Visuals

- Signed Distance Field
- Bilateral Smoothing
- Marching Cubes

Haptic Device(s)

1000 Hz

1000–3000 Hz

10 Hz

126x12 to 913x46

1004x12 to 1762x46

1764x254 to 1872x465

126x12 to 913x46

1180x969 to 1180x1066

1196x66 to 1755x948

1826x987 to 1920x1080

0x987 to 103x1080
Simulation: Haptics

Haptics

- Read Haptic Device Pose
- Render Virtual Coupling Forces

Physics

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Game Engine(s)

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Haptic Device(s)

- 1000 Hz
- 1000–3000 Hz
- 10 Hz
Haptics

- Two instances of the same tool \( (T_H, T_G) \)
- Interaction spring between real and virtual
  - Based on virtual coupling

\[
\ddot{f}_s = [p(T_G) - p(T_H)] k_t - [\ddot{v}(T_G) - \ddot{v}(T_H)] b_t
\]

\[
\ddot{r}_s = R \left( W H_{T_G} W H_{T_H}^{-1} \right) k_r - [\ddot{\omega}(T_G) - \ddot{\omega}(T_H)] b_r
\]
Improving Haptic Stability

- Additional damping terms

\[ \ddot{f}_s = [\mathbf{p}(T_G) - \mathbf{p}(T_H)] k_t - [\ddot{\mathbf{v}}(T_G) - \ddot{\mathbf{v}}(T_H)] b_t - \ddot{\mathbf{v}}(T_H) b_{t}^{abs} \]

\[ \ddot{\tau}_s = R \left( W H_{T_G} W H_{T_H}^{-1} \right) k_r - [\ddot{\omega}(T_G) - \ddot{\omega}(T_H)] b_r - \ddot{\omega}(T_H) b_r^{abs} \]

\[ \ddot{\tau}_s' = \ddot{\tau}_s - [(c - p_c) \times \dot{c}] b_r^{ext} \]
Improving Haptic Stability

• Force saturation: contacts and interaction
• High stiffnesses $\Rightarrow$ low felt inertia
• Low accelerations $\Rightarrow$ high sim. stability
Improving Haptic Stability

- Force saturation: contacts and interaction
- High stiffnesses $\Rightarrow$ low felt inertia
- Low accelerations $\Rightarrow$ high sim. stability

\[ \| \vec{f}_c \| < \| \vec{f}_s \| \]
Improving Haptic Stability

- Force saturation: contacts and interaction
- High stiffnesses ⇒ low felt inertia
- Low accelerations ⇒ high sim. stability
- Balance force magnitudes
Haptics Demonstration
Haptic Registration in VR

- Hand-tool alignment for skill transfer
- Use VR controller relative pose
Haptic Registration in VR
Simulation System

1. High-force haptic feedback ✓
2. Stepless haptic material removal ✓
3. Efficacy of HMD-based VR haptic simulators ☐
Applications

- Used my methods in 3 simulators

1. **HIPS**

2. **DynamicHIPS**

3. **DentalSim**
Hip Replacement Simulator

1. Kinesthetic haptic rendering for saw and reamer
   - Large forces during reaming

2. Hammering *impossible* to render on traditional hardware
   - New hardware with new rendering paradigm
Haptic Rendering of Hammering
Haptic Rendering of Hammering
### HIPS Expert Feedback

<table>
<thead>
<tr>
<th>Statement</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>The 3D visualization of the situs was realistic.</td>
<td></td>
</tr>
<tr>
<td>The 3D visualization of the OR was realistic.</td>
<td></td>
</tr>
<tr>
<td>The HIPS simulator helps in learning the implantation of a hip prosthesis.</td>
<td></td>
</tr>
<tr>
<td>Time was going by fast while I was using the HIPS simulator.</td>
<td></td>
</tr>
<tr>
<td>Getting accommodated to using the HIPS simulator was easy.</td>
<td></td>
</tr>
<tr>
<td>Using the HIPS simulator gave me great pleasure.</td>
<td></td>
</tr>
<tr>
<td><strong>I would recommend the HIPS simulator to medical students (last year of study).</strong></td>
<td></td>
</tr>
<tr>
<td><strong>I would recommend the HIPS simulator to residents (in training at hospital).</strong></td>
<td></td>
</tr>
<tr>
<td><strong>I would recommend the HIPS simulator to attending surgeons (completed training).</strong></td>
<td></td>
</tr>
<tr>
<td>The HIPS simulator should support preparation of patient-specific operations.</td>
<td></td>
</tr>
<tr>
<td>The sawing of the femur head was realistic.</td>
<td></td>
</tr>
<tr>
<td>Regarding the visualization: the sawing of the femur head looked realistic.</td>
<td></td>
</tr>
<tr>
<td>Regarding the haptics: the sawing of the femur head felt realistic.</td>
<td></td>
</tr>
<tr>
<td>The reaming of the acetabulum was realistic.</td>
<td></td>
</tr>
<tr>
<td>Regarding the visualization: the reaming of the acetabulum looked realistic.</td>
<td></td>
</tr>
<tr>
<td>Regarding the haptics: the reaming of the acetabulum felt realistic.</td>
<td></td>
</tr>
<tr>
<td>The hammering of the hip implant was realistic.</td>
<td></td>
</tr>
<tr>
<td>Regarding the visualization: the hammer of the hip implant looked realistic.</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>The hammering of the femur rasp was realistic.</td>
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**Rating**

- **Strongly disagree**
- **Disagree**
- **Neither**
- **Agree**
- **Strongly agree**
Bi-Manual Dental Simulator
HMD: Stereo Vision & Hand-Tool Alignment

- Effect of HMD VR
  
  - 3D rendering: **stereo 3D & monoscopic 3D**
  
- Hands & tools: **aligned & misaligned**

  - **Group 1: Stereo 3D & hand-tool alignment**
  - **Group 2: Monoscopic 3D & hand-tool alignment**
  - **Group 3: Stereo 3D & hand-tool misalignment**
  - **Group 4: Monoscopic 3D & hand-tool misalignment**

- Performance and learning effect
  
  - **Real** = plastic teeth
  
  - **Virtual** = simulator score
HMD: Stereo Vision & Hand-Tool Alignment
HMD: Stereo Vision & Hand-Tool Alignment

- Hand-tool alignment improves learning effect
  - By real-world measures

- Stereo 3D improves skill transfer
Gaze Analysis of Dental Students

- Can gaze behavior predict performance & learning?
- Custom eye tracking integration
  - Fast: 120 Hz
  - Accurate: 1.2° error
- Custom VR zoom feature
- Complex mirrored gaze on upper jaw
Gaze Analysis of Dental Students
Gaze Analysis of Dental Students

- Learning effectiveness high
- Formulated novel gaze-based metrics
  - Consistency of vision: vision breaks

![Graphs and scatter plots showing analysis results.](image-url)
Conclusions

• Intersection-free simulation with modular collision responses
• Fully stepless material removal
• Novel simulation system for rigid 6DOF tools
• First high-force surgical VR simulator
  • Automated VR-haptic registration
• Simulators’ learning efficacy objectively proven
  • Wide approval of usefulness & realism by dozens of surgeons & students
Future Works

- Effect of real-time feedback based on my gaze-metrics
- Simulate flexible tools, such as files for root-canals
  - Soft tissue deformation & cutting
- Compare with more expensive collision responses
  - E.g. constraints with global solvers


Publications (Coauthor)


Immersive Medical VR Training Simulators with Haptic Feedback

Maximilian Kaluschke

Introduction  Collision  Contact  Material  Haptics  DentalSim  HIPS  Conclusions