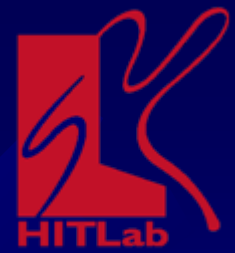
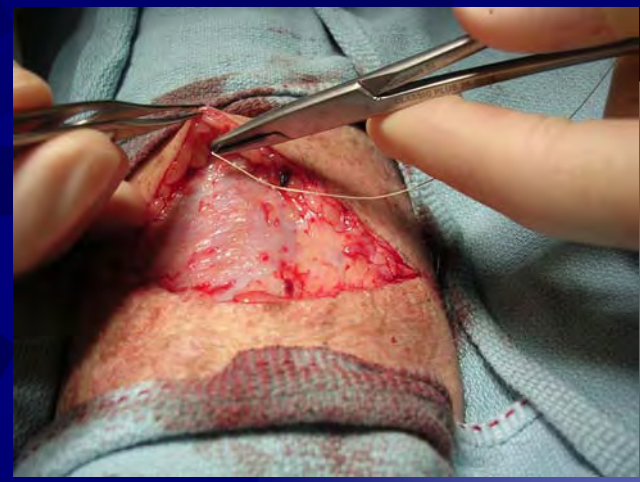


Fast Update Procedures for a Finite Element Based Surgical Suturing Simulator

Alex J. Lindblad
Human Interface Technology Lab
Department of Civil and Environmental Engineering
University of Washington
June 21, 2006

Surgical Suturing

- Bi-manual Interaction
- Tissue Cutting
- Tissue Removal
- Skin Undermining
- Skin Repositioning
- Suture Placement
- Multiple Suture Types



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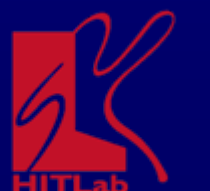
Current Training / Assessment Methods

- Pig's feet
- Cadaver tissue
- Chicken
- Synthetic tissue models
- Feedback from doctor or student
- Qualitative

Is there a better way?



Suturing Simulator

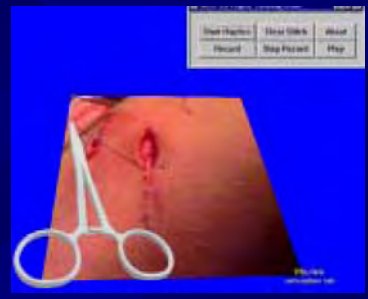
A virtual environment that allows medical students and medical doctors to learn basic suturing skills, practice individual components of medical suturing, and have their suturing abilities assessed using non-biased qualitative and quantitative methods.

Simulator Components

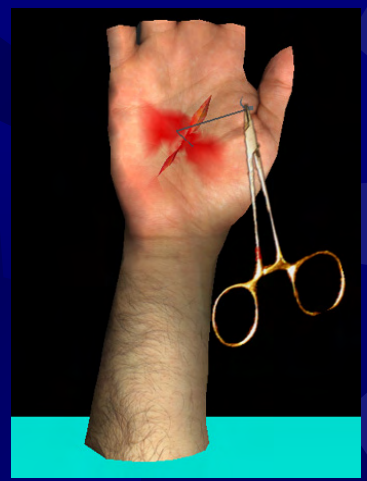
- Graphical Interface – 30 Hz
- Tactile Feedback (Haptics) – 1KHz
- Collision Detection
- Deformation Model

Previous Simulators

- Bi-manual
- Tissue Cutting
- Tissue Removal
- Skin Undermining
- Skin Repositioning
- Suture Placement
- Multiple Suture Types



Mass-Spring Based
Webster et al



Finite Element Based
Berkely et al

Next Generation

- Bi-manual
- Tissue Cutting
- Tissue Removal
- Skin Undermining
- Skin Repositioning
- Suture Placement
- Multiple Suture Types

Difficulties

- Bi-manual Interaction
  - parallel process
- Tissue Cutting
  - topological changes
- Skin Undermining
  - separate behavior
- Needle / Suture Modeling
  - embedded interaction

Berkley et al

Goals of Prototype

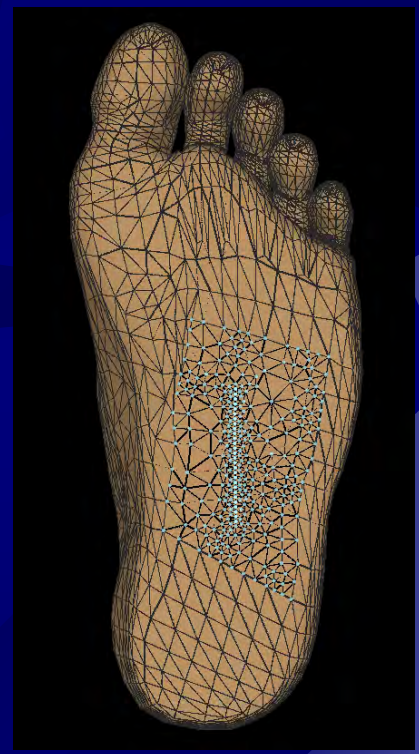
- Bi-manual interaction
- Real-time finite element solution engine
  - tissue cutting, skin undermining, more accurate suture placement
- Single CPU

Architecture

- C++ - Computational Code
- FLTK - Graphical Interface
- OpenGL – Graphics
- Multiple Threads
- Various Libraries
  - SOLID, ATLAS, LAPACK, OpenHaptics

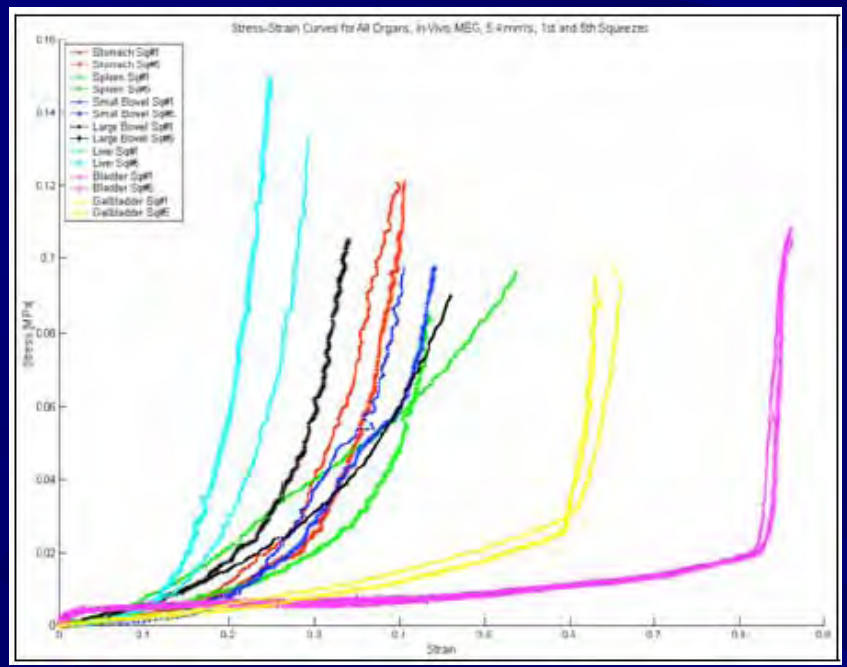
Finite Element Model

- Multiple element types
  - Skin – CST
  - Tissue – Linear Wedge
- Constraints
  - Tool-tissue interaction
  - Cuts
  - Sutures



Material Models

- Linear elastic
- Exponential hyper elastic



Brown

Governing Equation

- Standard finite element, Ku = f
- Constraint based

$$\begin{bmatrix} \mathbf{K} & \mathbf{C}^T \\ \mathbf{C} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{v} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f} \\ \mathbf{g} \end{Bmatrix}$$

$$\mathbf{K} \equiv n \times n \qquad \mathbf{C} \equiv m \times n$$

Solution Strategy

$$\begin{bmatrix} \mathbf{K} & \mathbf{C}^T \\ \mathbf{C} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{v} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f} \\ \mathbf{g} \end{Bmatrix}$$

$$\mathbf{K}\mathbf{u} = \mathbf{f} - \mathbf{C}^T\mathbf{v}$$

$$\mathbf{C}\mathbf{K}^{-1}\mathbf{C}^T\mathbf{v} = \mathbf{C}\mathbf{K}^{-1}\mathbf{f} - \mathbf{g}$$

$$\mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^T$$

Solution Strategy

$$\begin{bmatrix} \mathbf{K} & \mathbf{C}^T \\ \mathbf{C} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{v} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f} \\ \mathbf{g} \end{Bmatrix} \qquad \mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^T$$

$$\mathbf{u} = \mathbf{K}^{-1}\left[\mathbf{f} - \mathbf{C}^T\mathbf{v}\right]$$

$$\mathbf{v} = \mathbf{S}^{-1}\left[\mathbf{C}\mathbf{K}^{-1}\mathbf{f} - \mathbf{g}\right]$$

- Precompute various products
- Predefine the number of constraints

Constraint Change

- Initial tool-tissue contact
- Tool removal
- Tissue cutting
- Suture placement

$$\mathbf{u} = \mathbf{K}^{-1}\left[\mathbf{f} - \mathbf{C}^{T}\mathbf{v}\right] \qquad \mathbf{v} = \mathbf{S}^{-1}\left[\mathbf{C}\mathbf{K}^{-1}\mathbf{f} - \mathbf{g}\right]$$

$$\mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^{T}$$

Constraint Removal

$$\mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^{T}$$

- Do not change size of C or S
- Zero out row *i* in C
- Place zeros in row *i* and column *i* of S
- Place a one in the diagonal of S

$$\mathbf{S}_0 = \mathbf{S} + \mathbf{M}\mathbf{N}^{T}$$

$$\mathbf{M} = \left[\mathbf{e}_i - \mathbf{S}\mathbf{e}_i \middle| \mathbf{e}_i\right] \qquad \mathbf{N} = \left[\mathbf{e}_i \middle| S_{ii}\mathbf{e}_i - \mathbf{S}^{T}\mathbf{e}_i\right]$$

Constraint Removal

$$\mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^{T}$$

$$\mathbf{S}_0 = \mathbf{S} + \mathbf{M}\mathbf{N}^{T}$$

$$\mathbf{M} = \left[\mathbf{e}_i - \mathbf{S}\mathbf{e}_i \,\middle|\, \mathbf{e}_i\right] \qquad \mathbf{N} = \left[\mathbf{e}_i \,\middle|\, S_{ii}\mathbf{e}_i - \mathbf{S}^{T}\mathbf{e}_i\right]$$

- Reduces to a rank-1 update of S^{-1} using the Sherman-Woodbury formula (Gondzio, 1995)

$$\mathbf{S}_0^{-1} = \mathbf{S}^{-1} + \mathbf{e}_i\mathbf{e}_i^{T} - \frac{1}{\mathbf{e}_i^{T}\mathbf{S}^{-1}\mathbf{e}_i}\mathbf{S}^{-1}\mathbf{e}_i\mathbf{e}_i^{T}\mathbf{S}^{-1}$$

Constraint Addition

$$\mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^{T}$$

- Populate row *i* in C with constraint
- Propagate change in S

$$\mathbf{S}_0 = \mathbf{S} + \mathbf{M}\mathbf{N}^{T}$$

$$\mathbf{M} = \left[\mathbf{e}_i \;\middle|\; -\mathbf{s}\right] \qquad \mathbf{N} = \left[-\mathbf{e}_i \;\middle|\; \mathbf{s} - s_i\mathbf{e}_i\right]$$

$$\mathbf{s} = \mathbf{C}\mathbf{K}^{-1}\mathbf{c}_s^{T} \qquad s_i = \mathbf{s}(i)$$

Constraint Addition

$$\mathbf{S} = \mathbf{C}\mathbf{K}^{-1}\mathbf{C}^{T}$$

$$\mathbf{S}_0 = \mathbf{S} + \mathbf{M}\mathbf{N}^{T}$$

$$\mathbf{M} = \left[\mathbf{e}_i \; -\mathbf{s} \middle| \mathbf{e}_i\right] \qquad \mathbf{N} = \left[-\mathbf{e}_i \middle| \mathbf{s} - s_i\mathbf{e}_i\right]$$

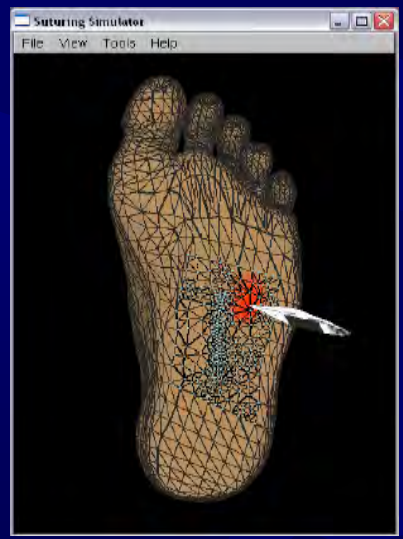
$$\mathbf{s} = \mathbf{C}\mathbf{K}^{-1}\mathbf{c}_s^{T} \qquad s_i = \mathbf{s}(i)$$

- Woodbury formula

$$\mathbf{S}_0^{-1} = \mathbf{S}^{-1} - \left[\mathbf{S}^{-1}\mathbf{M}\left(\mathbf{1} + \mathbf{N}^{T}\mathbf{S}^{-1}\mathbf{M}\right)^{-1}\mathbf{N}^{T}\mathbf{S}^{-1}\right]$$

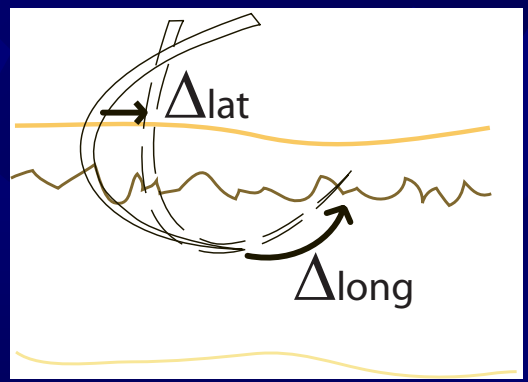
Forceps Interaction

- Modeled as a single point of contact
- Stylus switch indicates open / closed
- Constraint removed if stylus is on and reaction force is tensile.

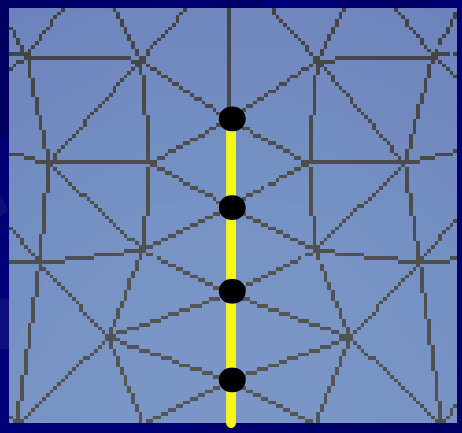


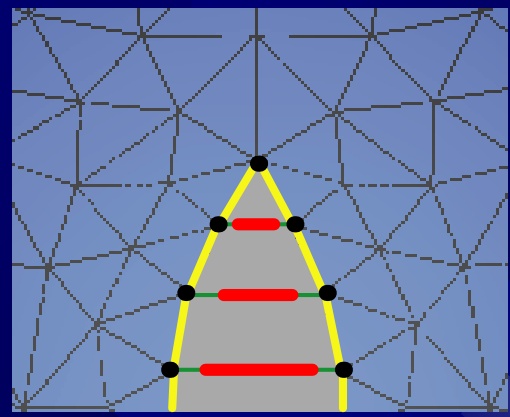
Needle Interaction

- Initial Interaction - Single point of contact
- Puncture – force vs. stress
- Embedment



Scalpel Interaction - Cutting

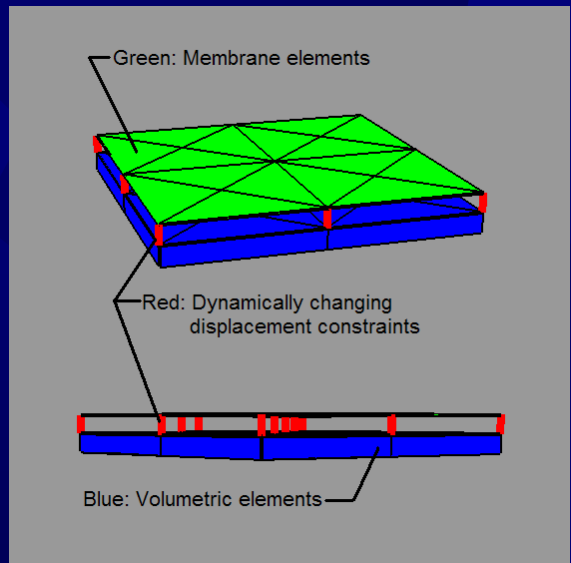




- Cut starts once scalpel has overcome puncture stress (force) of skin
- As scalpel passes over nodes, constraints are removed
- Empirical resisting force

Skin Undermining

- Create duplicate nodes for skin elements
- Add constraints to bind skin and subcutaneous tissue together
- Cut away skin in same manner as tissue cutting



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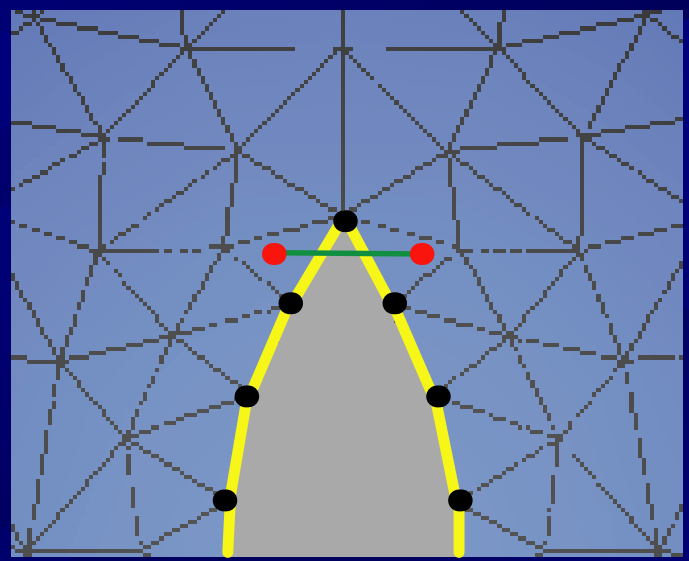
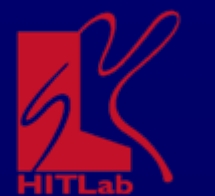
Suture Model

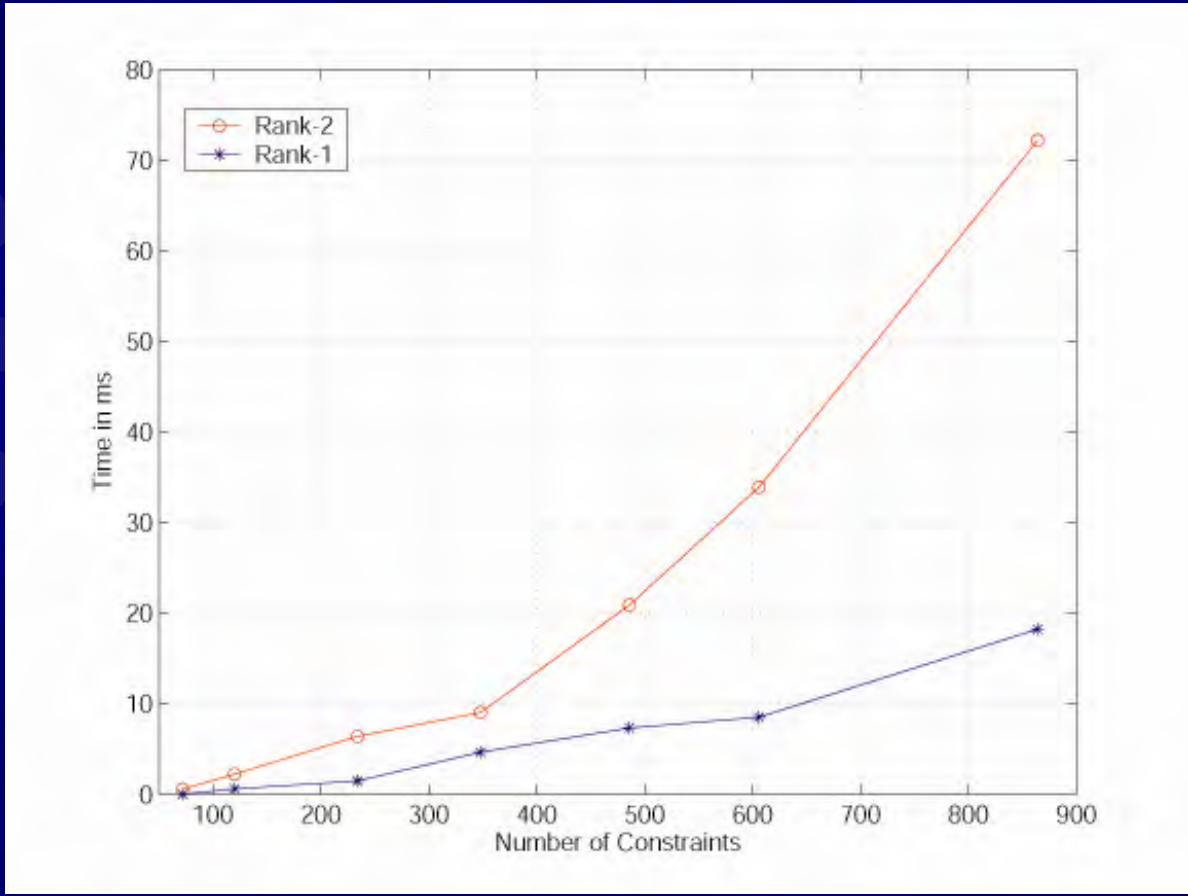
- Defined by entry and exit point
- Displacement constraint



Feasible?



Timing Tests



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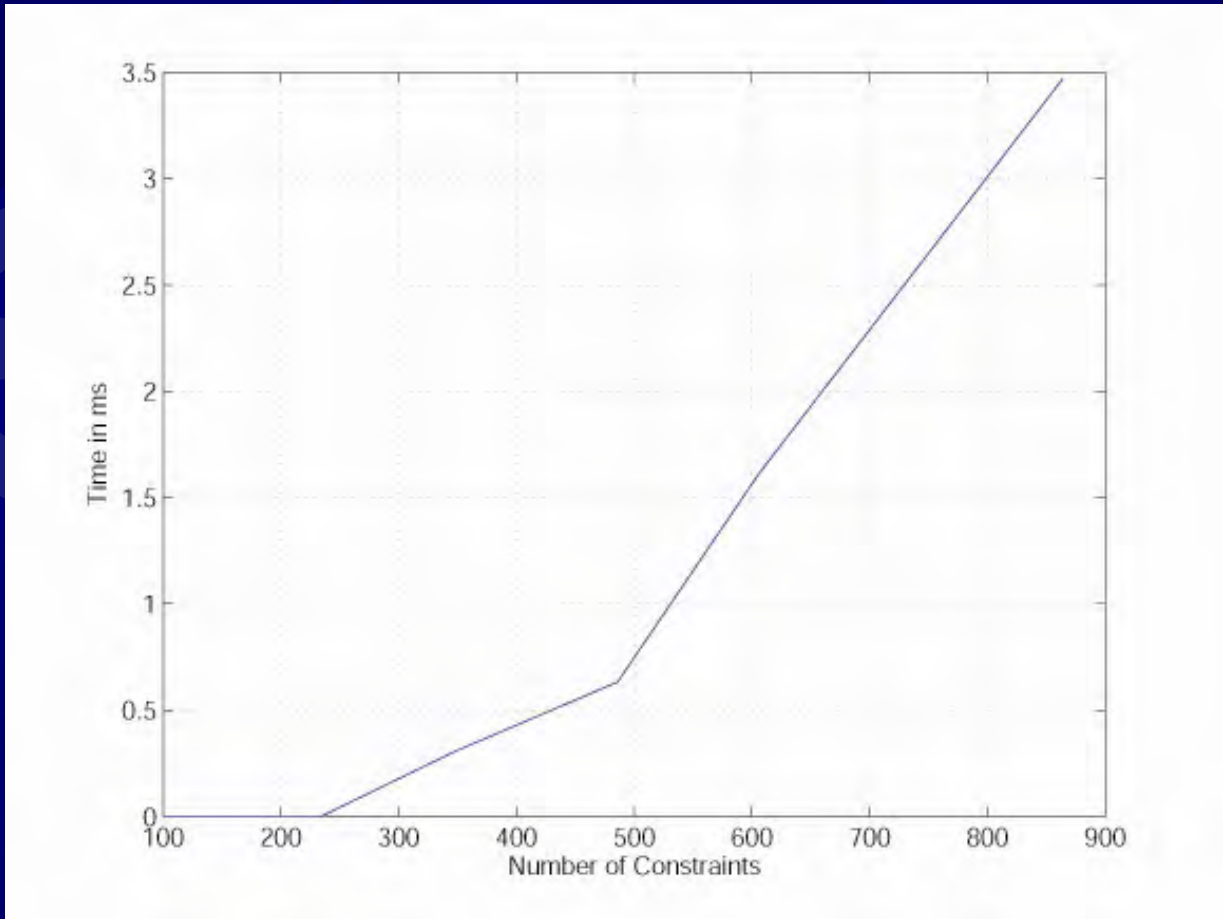
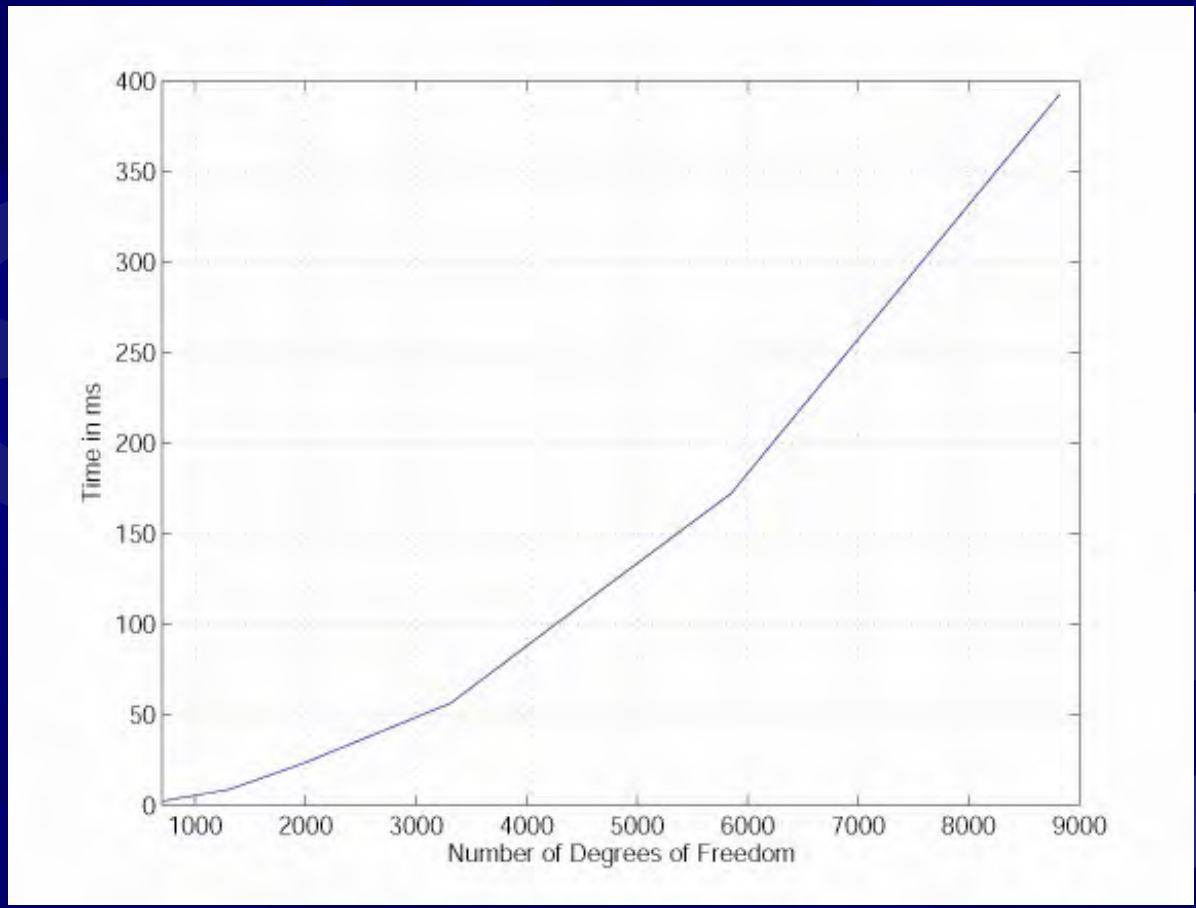
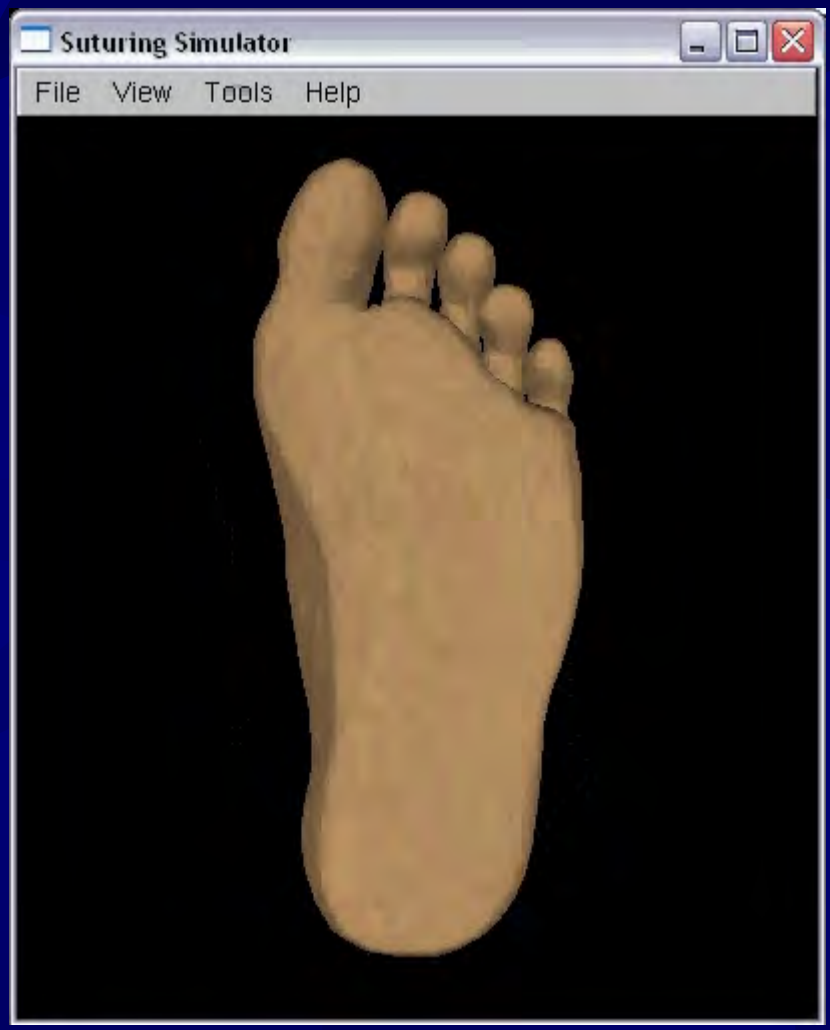


Timing Tests




File


Suturing Simulator
File
View
Tools
Help

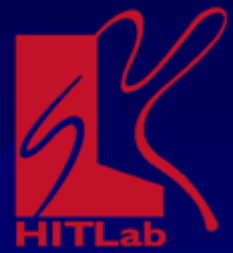
Impact

- Advances state-of-the-art in suturing simulation
- Creates a real-time FE platform for use in:
  - Games
  - Engineering proof of concept
  - Education

Conclusions / Future Work

- Developed real-time FE solution engine
- Created methods to add/remove constraints interactively
  - Tissue cutting, skin undermining, suturing
- Implemented prototype to test methods

- Improve threading behavior (make parallel)
- Use integrated haptics (Mimic Mantis / Workbox)
- Increase model capabilities
  - Skin repositioning
  - Tissue removal
  - Multiple suture types



Acknowledgements

Department of Energy's Computational Science Graduate Fellowship

Questions?