NA-MIC
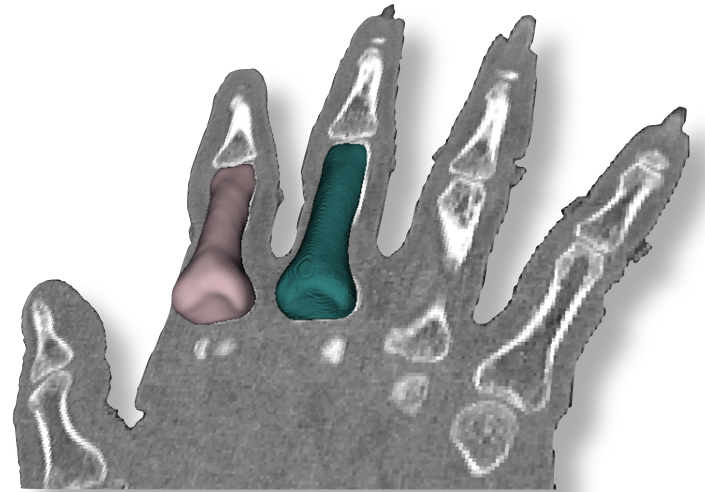*National Alliance for Medical Image Computing*
http://na-mic.org

Image to Finite Element Mesh: An End to End Workflow

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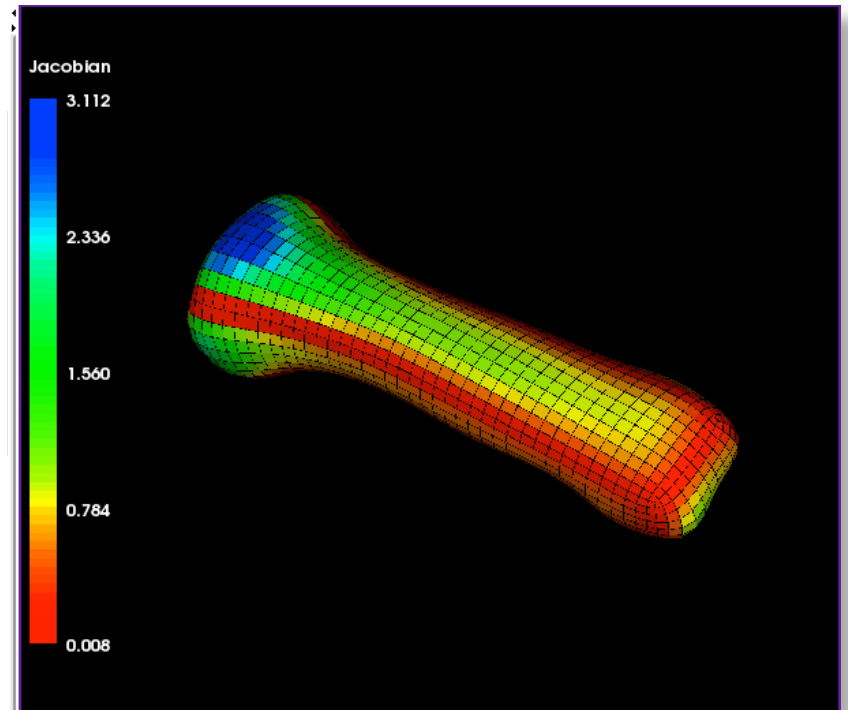
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NA-MIC Tutorial Contest: Summer 2010

Learning Objective

After following this tutorial, you will be able to use Slicer3 to execute a full workflow from a source image all the way through the creation and evaluation of an object's 3D volumetric finite element (FE) mesh

Pre-requisites

- This tutorial assumes the user is familiar with loading image datasets and creating basic labelmaps in Slicer. Please consult the following prerequisite material if you want to brush up on these skills first:

  – Data Loading & Visualization tutorial
  - Sonia Pujol, Ph.D., Harvard/SPL
  - http://www.slicer.org/slicerWiki/images/c/c9/3DDataLoadingAndVisualization_Slicer3.6_SoniaPujol.pdf
  – User documentation for the Slicer3 Editor module
  - Steve Pieper, Ph.D, Harvard/SPL, Isomics
  - http://www.slicer.org/slicerWiki/index.php/Modules:Editor-Documentation-3.6

Pre-requisites

- The user may use hand segmentation or any segmentation algorithm to create surfaces for meshing. One of the simplest algorithms to use is Slicer3's Fast Marching Segmentation module:

- Fast Marching Segmentation documentation
  - Adriy Fedorov, Ph.D., Harvard/SPL
  - http://www.slicer.org/slicerWiki/index.php/Modules:FastMarchingSegmentation-Documentation-3.6

Material

- This tutorial requires the installation of the **Slicer3.6 release** and the tutorial dataset. They are available at the following locations:

- **Slicer3.6** download page

  – http://www.slicer.org/pages/Downloads/

- **Tutorial dataset**: [name of dataset]

  – http://www.slicer.org/slicerWiki/index.php/File:IAFEMeshData-TutorialContestSummer2010.zip

Disclaimer: *It is the responsibility of the user of Slicer to comply with both the terms of the license and with the applicable laws, regulations, and rules.*

Material

- A Users Guide is available for the IA-FEMesh module, which covers the step by step process of mesh creation.

- For additional assistance, consult the Users Guide available here

  - https://mri.radiology.uiowa.edu/downloads/IA-FEMesh_Manual_version1.pdf

Material

- **Interactive screencasts showing the following operations are available from the NA-MIC wiki website:**
- Creating and importing a Slicer model
  - http://wiki.na-mic.org/Wiki/index.php/File:Meshing-1-labelmap-model-import.mov
- Simple Editing of Building Blocks around a surface
  - http://wiki.na-mic.org/Wiki/index.php/File:Meshing-2-building-blocks.mov
- Creating a mesh from a surface and building blocks
  - http://wiki.na-mic.org/Wiki/index.php/File:Meshing-3-mesh-creation.mov
- Evaluating and Improving Mesh Quality
  - http://wiki.na-mic.org/Wiki/index.php/File:Meshing-4-mesh-quality-tab.mov

Platform

- The IA-FEMesh Slicer3 Module was developed using both Linux (32 and 64 bit) and Mac (OS X 10.4 - 10.6)

- The module has been tested on both Linux 64-bit and Mac (OS X 10.6)

Overview

In this tutorial, we will…

- Create a labelmap and a corresponding surface model of a structure of interest from a source image

- Import the surface model into the IA-FEMesh module

- Interactively create a volumetric hexahedral mesh of the object of interest

- Examine and improve the quality of the mesh

- Export the mesh for continued processing in a commercial finite element solver (e.g. Abaqus)

- Review the steps to create an object mesh from imagery source

Loading Image Data

1. Select the Slicer3 Volume Module

2. Select the "Volume File" button to choose a file from the filesystem. Many image formats are supported.

3. Hit "Apply" to read the image into the current session
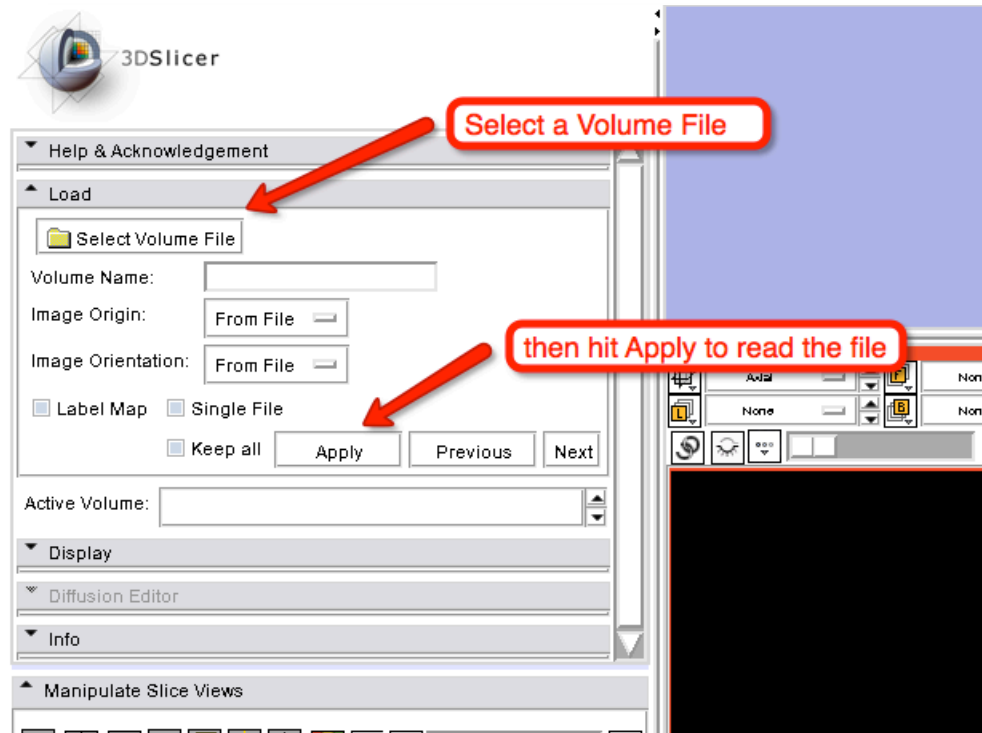
Creating a Labelmap

- A labelmap is a special type of volume where each voxel contains a code indicating the object to which the voxel belongs

- Labelmaps are loaded and saved like images, but handled differently by Slicer because of their purposes as indicators

- At right, we see a labelmap indicating the presence of the finger bone superimposed over corresponding background voxels from a CT image of the finger

Creating a LabelMap

- In Slicer3, a region of interest can be selected by hand or with an algorithm. The Slicer3 Editor module and the Fast Marching Segmentation module are two of the easiest ways to create labelmaps

- The Editor provides a palette of tools to interactively select regions of an image:

  – Level Tracing automatically selects nearby voxels similar to the selected point

  – The paintbrush is a way to clean up or add missing voxels after Level Tracing

Check Points
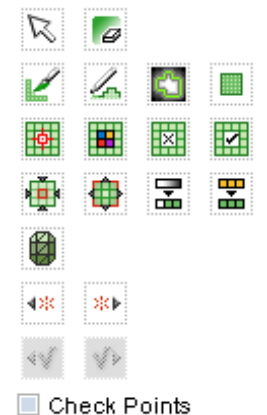
Creating a LabelMap

- Select the Level Tracing tool, move it around on the image, and click repeatedly to select the desired region

- Repeat the voxel selection operations for each slice containing the object to be segmented
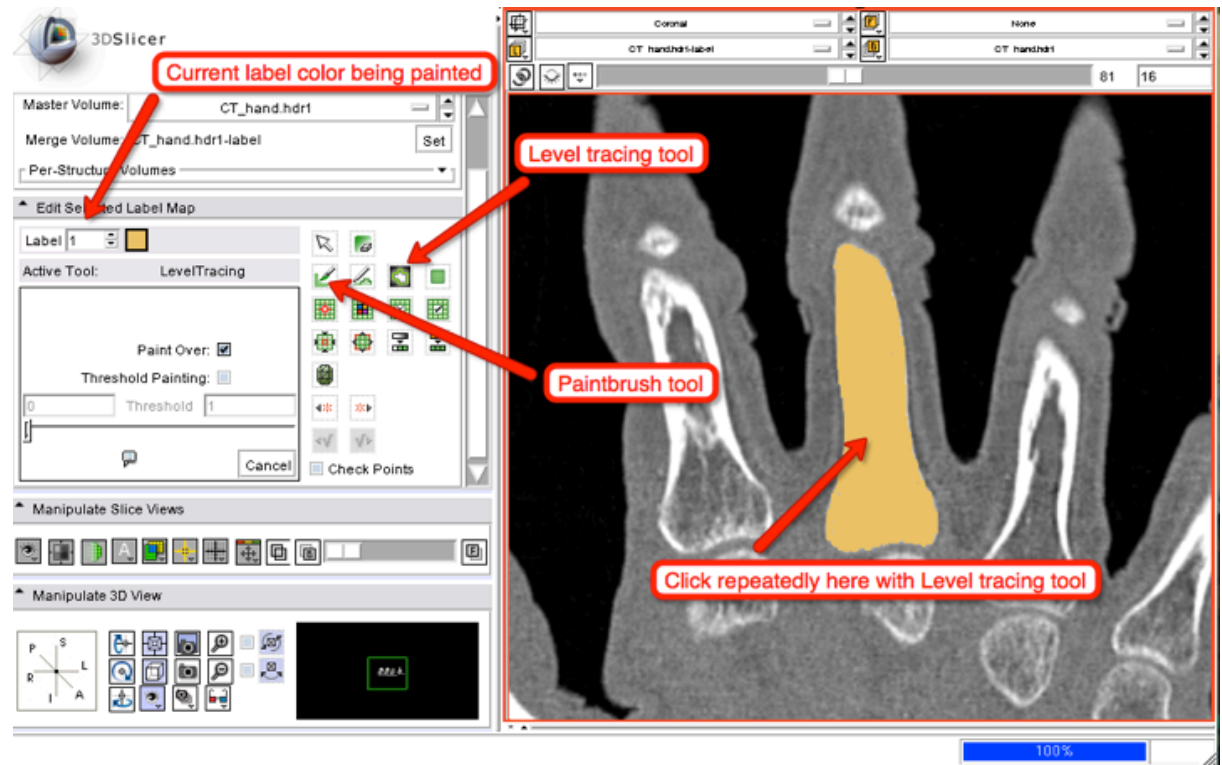
More about Segmentation

- Clearing unwanted voxels can accomplished by painting with the clear label color (label=0)

- Step-by-step instructions for using the Slicer3 Editor are available on the Slicer wiki site:

  – http://www.slicer.org/slicerWiki/index.php/Modules:Editor-Documentation-3.6

- A screencast is available which demonstrates labelmaps and shows how models are created:

  – http://wiki.na-mic.org/Wiki/index.php/File:Meshing-1-labelmap-model-import.mov

Smoothing the Label

- After editing is complete, smooth the labelmap to reduce jagged edges on the voxel contour

- A smooth label boundary generates the best quality final mesh
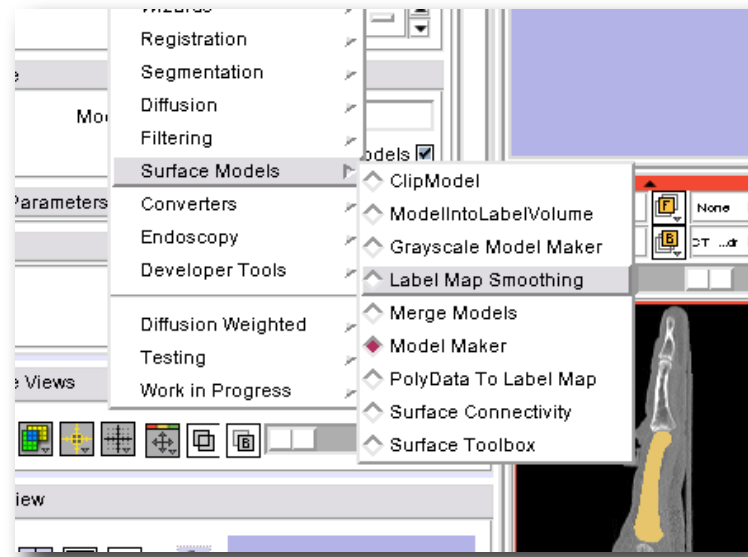
Create a Boundary Surface

- Once labelmap editing is complete, a boundary detection algorithm is run to wrap a contour around the labelmap

- Select the ModelMaker module to create the surface
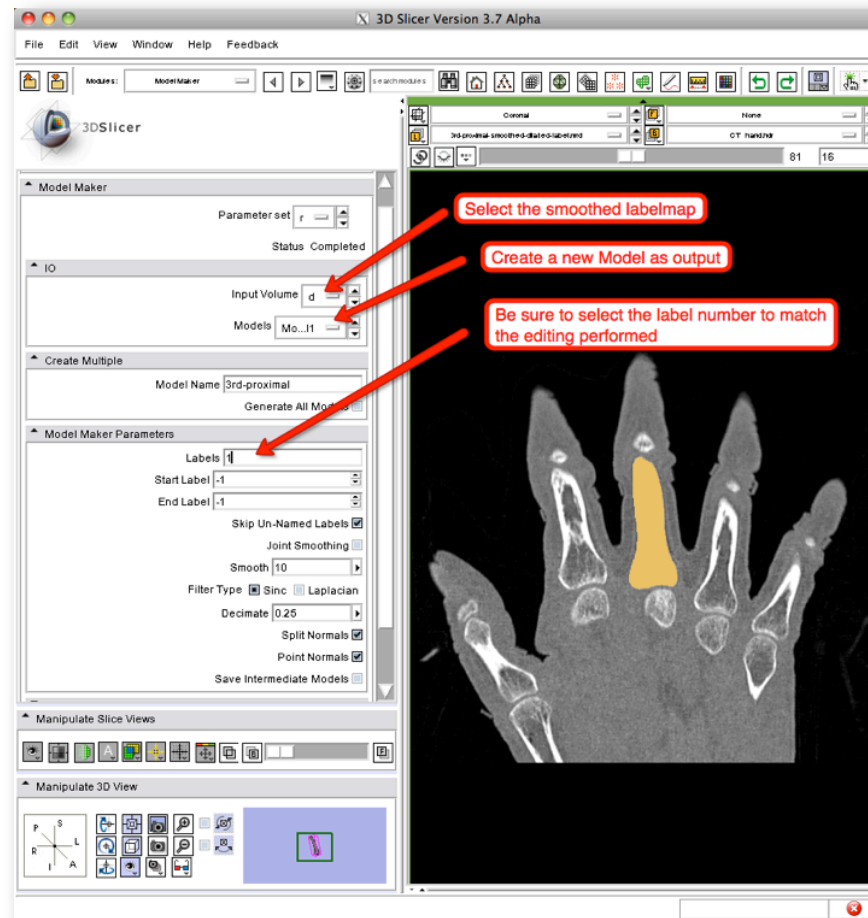
Smooth Even More?

- The Surface Toolbox can smooth the polygonal surface of the model further if needed

- Remember, a smooth boundary makes for higher quality boundary elements in the volume mesh
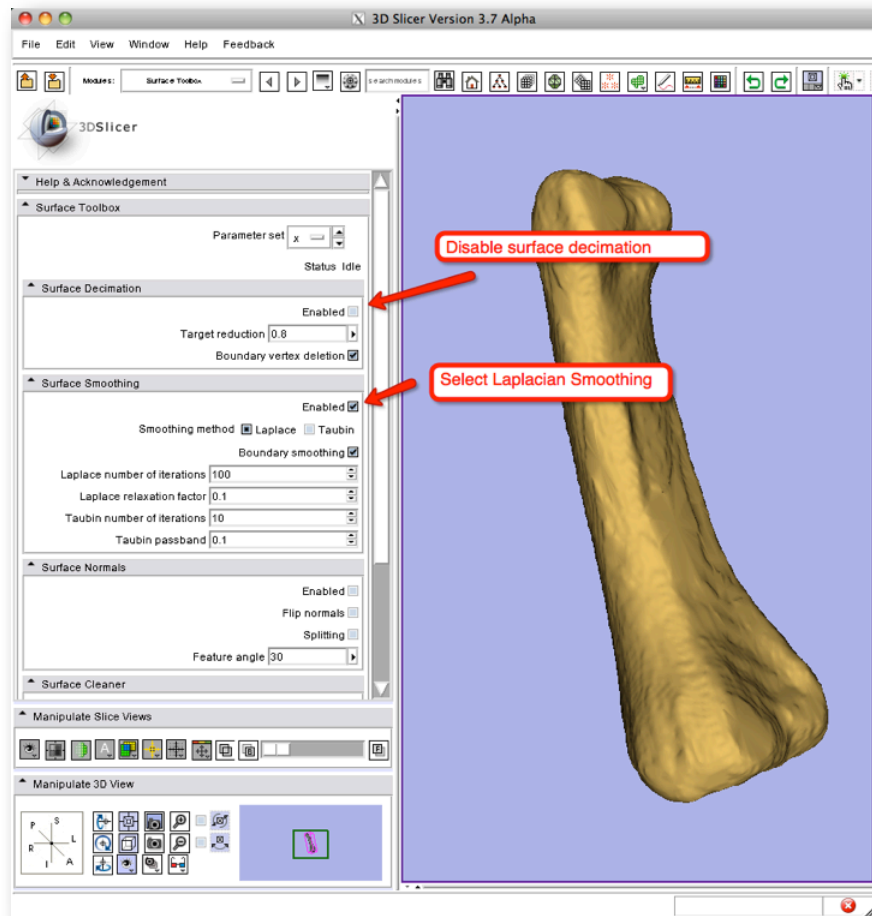
Loading a Surface

- The IA-FEMesh specific part of the workflow can begin with a surface loaded from an external file OR

- a Slicer3 Model is imported from the current Slicer3 session

STL, VTK, or VTP file

Current Slicer3 Session (MRML Scene)

Import Model
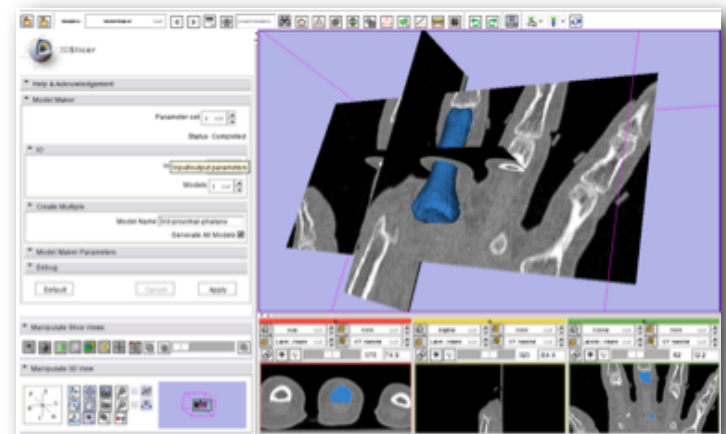
Importing a Surface Model

- Any Model object in the current Slicer MRML scene can be imported into the meshing module to start a meshing workflow

- Select the **Import Model** selection from the **Surface** tab in IA-FEMesh
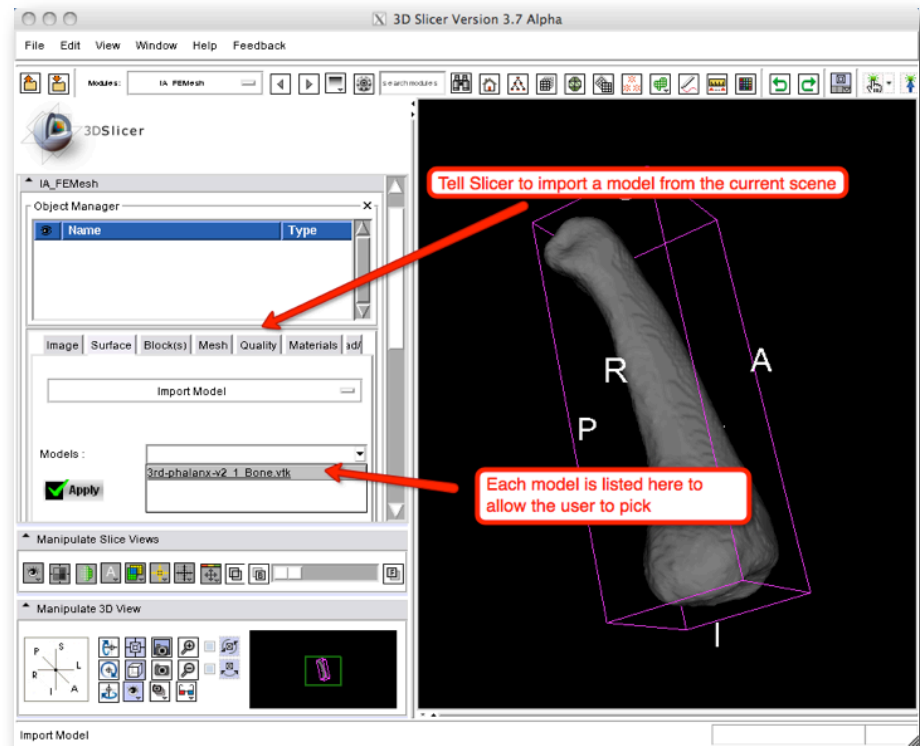
Creating a Building Block

- The surface is surrounded by Building Blocks to represent the shape to the meshing algorithm

- Building blocks are made through an interactive widget editing process

- Please refer to the screencast as an example of the steps:

  - http://wiki.na-mic.org/Wiki/index.php/File:Meshing-2-building-blocks.mov

Creating a Building Block

1. Select the **Block(s)** Tab
2. Select **Create** from the drop down menu
3. Check **Create Block from Surface Bounds**
4. Click **Apply**
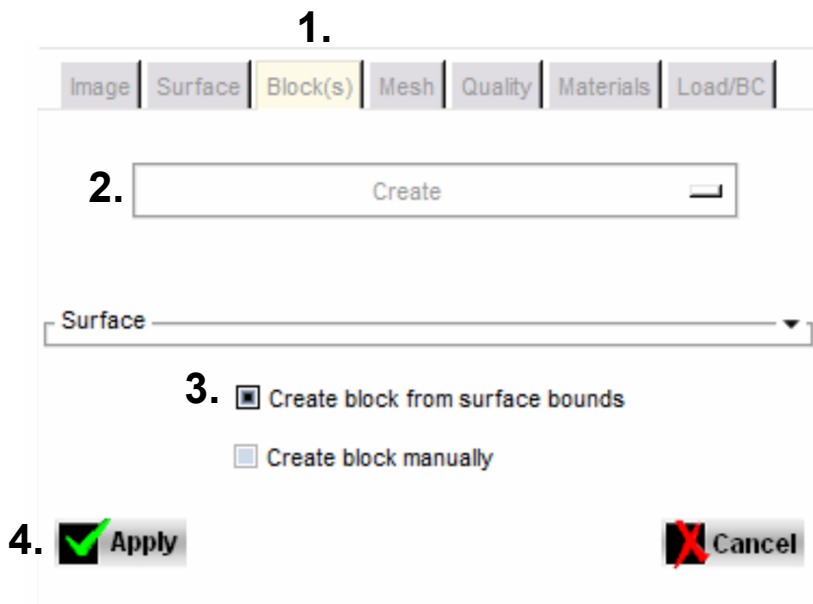
Sample Generated Building Block
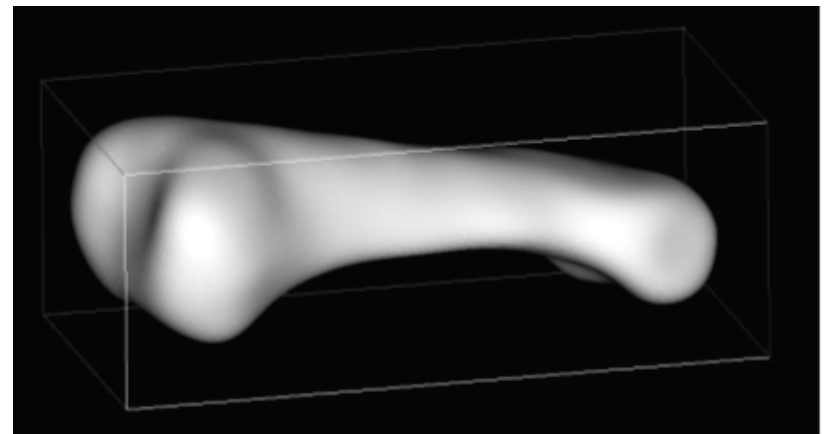
Manipulating the Building Block

1. Select the **Blocks** tab
2. Select **Build/Edit** from the drop down menu
3. Select the [hand icon] m the building blocks toolbar
   a) Allows manipulation of vertices, edges, and faces of building blocks
   b) Red spheres will appear at the vertices. The size of these spheres can be scaled

1.

Image	Surface	Block(s)	Mesh	Quality	Materials	Load/BC

Create
Load
✔ Build/Edit
Delete
Save

2. Build/Edit

3a.

[toolbar icons]

3b. Scale Spheres: [ ]
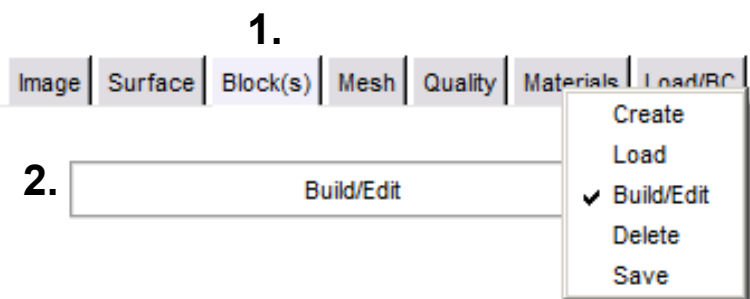
Manipulating the Building Block(2)

4. To move a vertex or face, simply click the **left mouse button** and drag it to the desired position

5. To move an edge, click the **middle mouse button** and drag it to the desired position

6. Click **Cancel** to exit building block manipulation

7. To save the building block, select **Save** from the drop down menu

- Note:
  - Active elements turn green
  - Inactive elements remain red
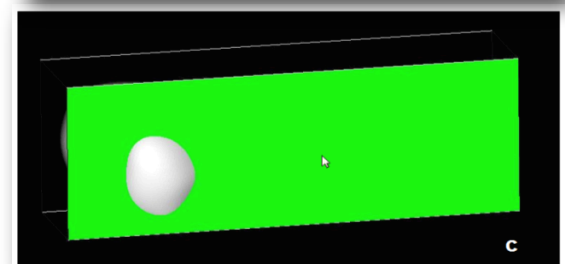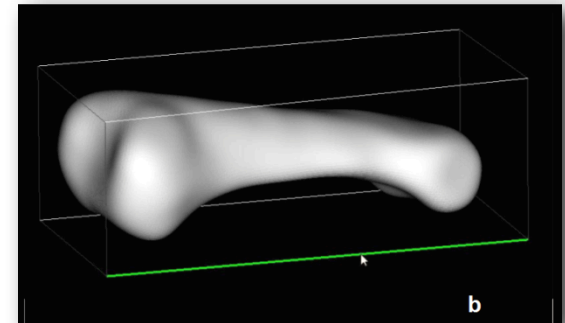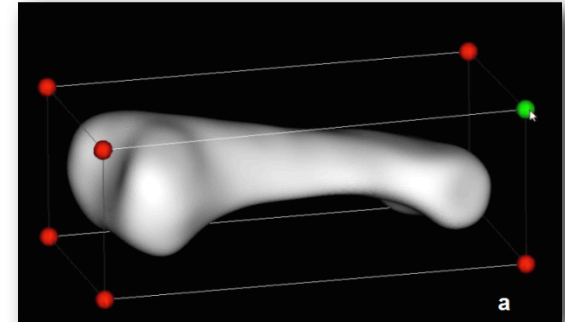
Creating a Mesh

- The surface imported into IA-FEMesh along with the building block surrounding the surface are used to create the mesh

- Mesh elements are created by projecting the bounding box mesh seeds through the volume

- Please refer to the screencast as an example of the process:

    – http://wiki.na-mic.org/Wiki/index.php/File:Meshing-3-mesh-creation.mov

Assigning Mesh Seeds

1. Select the **Mesh** tab
2. Select **Assign/Edit Mesh Seeds** from the drop down menu
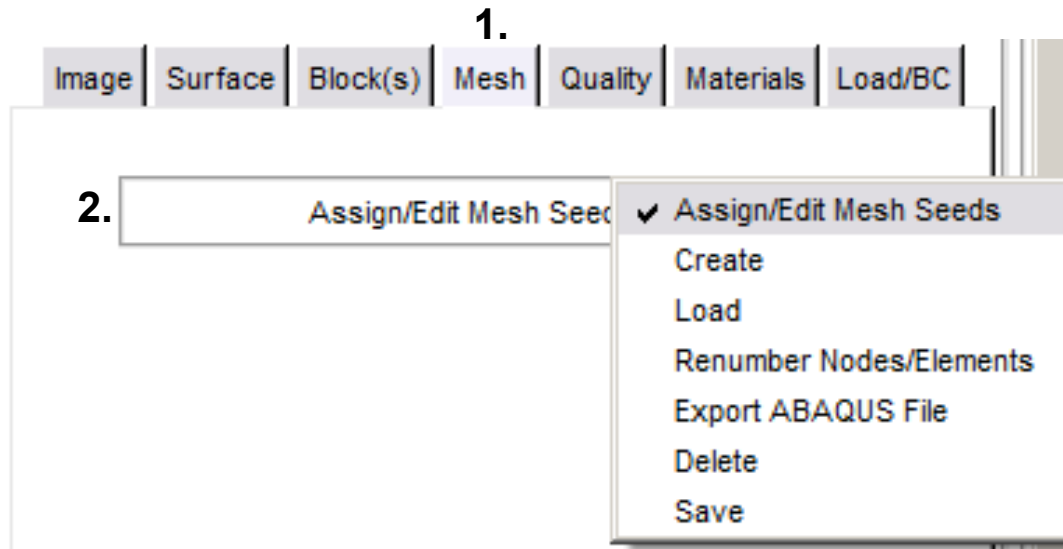
Assigning Mesh Seeds (2)
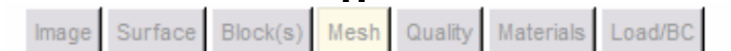
3. Select the [Color Code Mesh Seeds] button to visualize the distribution of mesh seeds

4. To change this assignment, select either **Element Length** or **Number of Divisions** from the drop down menu.

5. Click on a block with the left mouse button

6. Enter the values of your choice

7. Select **Apply**

8. Select **Cancel** to exit the mesh seeds operation

3. [Color Code Mesh Seeds]

4. Element Length

✓ Element Length
Number of Divisions

6. Rx: 1   Gy: 1   Bz: 1

7. ✓Apply

8. ✗Cancel

5.
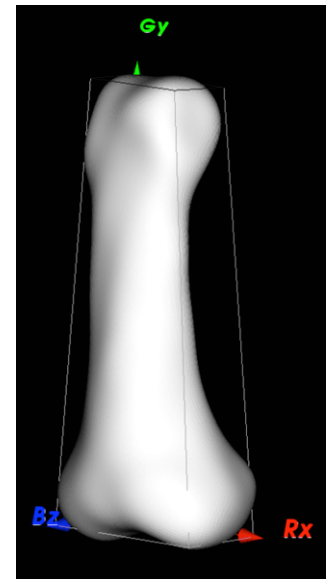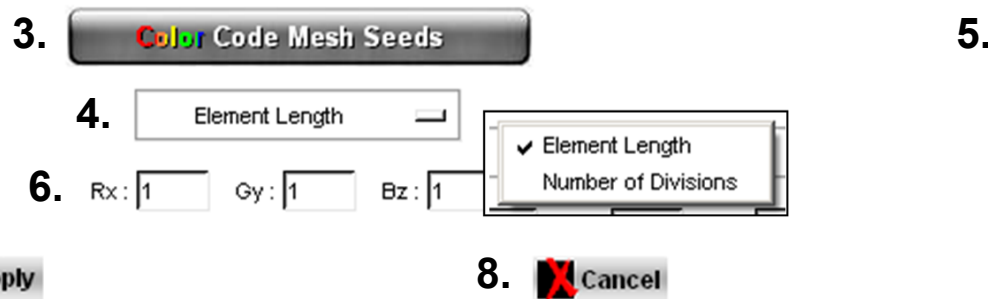
Creating a Mesh

1. Select the **Mesh** tab
2. Select **Create** from the drop down menu
3. Select **Volumetric Mesh**
4. Select **Building Block** in the following drop down menu
5. Provide starting **node/element numbers** and a **descriptive label** to be associated with the mesh definition
6. Selection **Elliptical** in the Interpolation drop down menu
7. Uncheck **Perform Smooth** for the initial attempt
8. Select **Apply** to generate the mesh

Check Mesh Quality

- Once mesh creation is complete, advance to the Quality tab on the interface to review the quality according to several metrics

- The process is demonstrated in the following screencast

  - http://wiki.na-mic.org/Wiki/index.php/File:Meshing-4-mesh-quality-tab.mov

Checking Mesh Quality

1. Select the **Quality** tab
2. Select **Evaluate/Display Mesh Quality** from the drop down menu
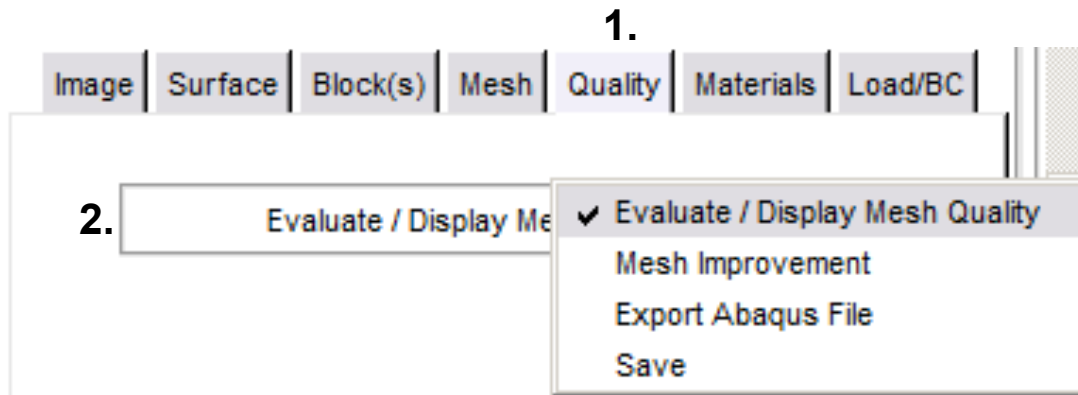
Checking Mesh Quality (2)

3. Select your **Metric of Choice** from the Metric drop down menu
4. Click the [Summary Report] button
5. Close summary report window after viewing
6. Click **Cancel** to exit the mesh quality check module

Check Interior Elements

- Use the Cut Plane button to examine interior elements and dragging the plane interactively
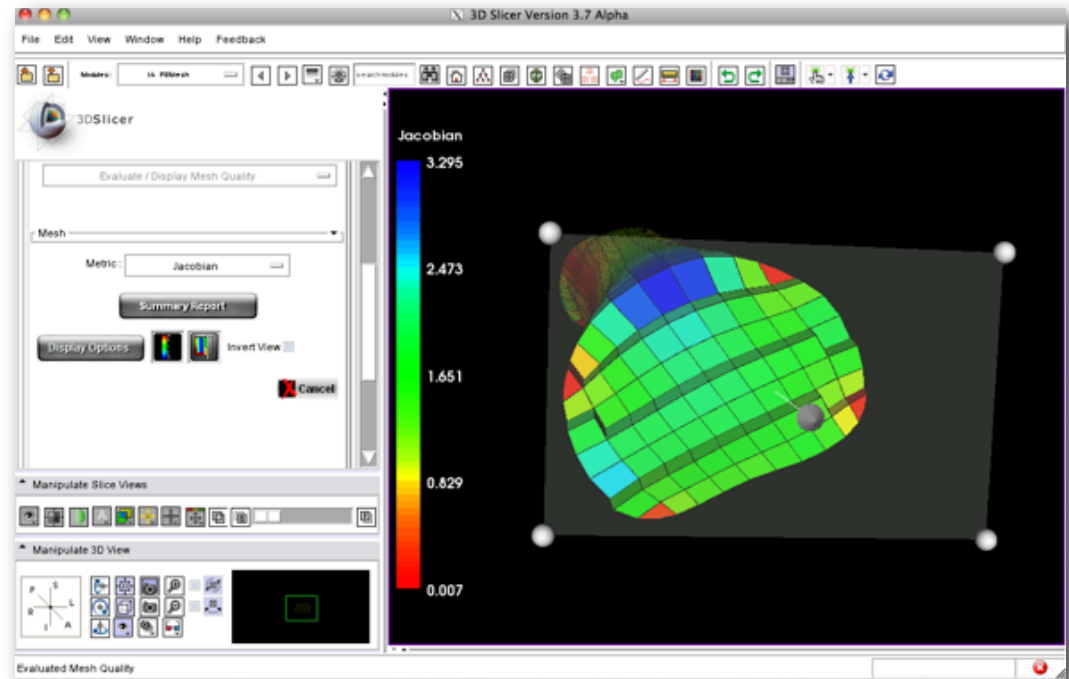
Improving Mesh Quality

1. Select the **Quality** tab
2. Select **Mesh Improvement** from the drop down menu
3. Check to ensure that the surface, block, and mesh of interest populate the **Mesh Component** frame
4. Select an **interpolation method** from the Interpolation drop down menu
5. Enter the desired **number of smoothing iterations** for the external nodes
6. Click **Apply**
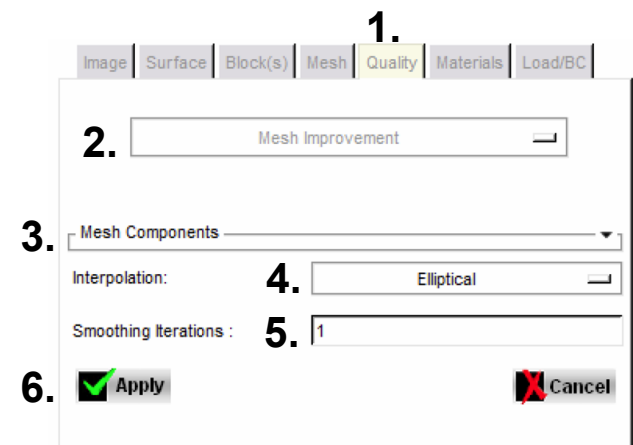
Improving Mesh Quality (2)

7. Adjust the smoothing parameters by toggling between the **Evaluate/Display Mesh Quality** and **Mesh Improvement** operations until the desired mesh is achieved

After Mesh Generation

- After mesh generation is complete, the user can add material properties and loading conditions to prepare for external finite element solver execution

- The following slides cover these options. For additional detail, refer to the IA-FEMesh Users Guide

  - https://mri.radiology.uiowa.edu/downloads/IA-FEMesh_Manual_version1.pdf

Assigning Material Properties

1. Select the **Materials** tab
2. Select the **User-Defined** option from the main menu
3. To add additional element sets, press [Element Set Definitions]
   *   A number of options are available for selecting element sets
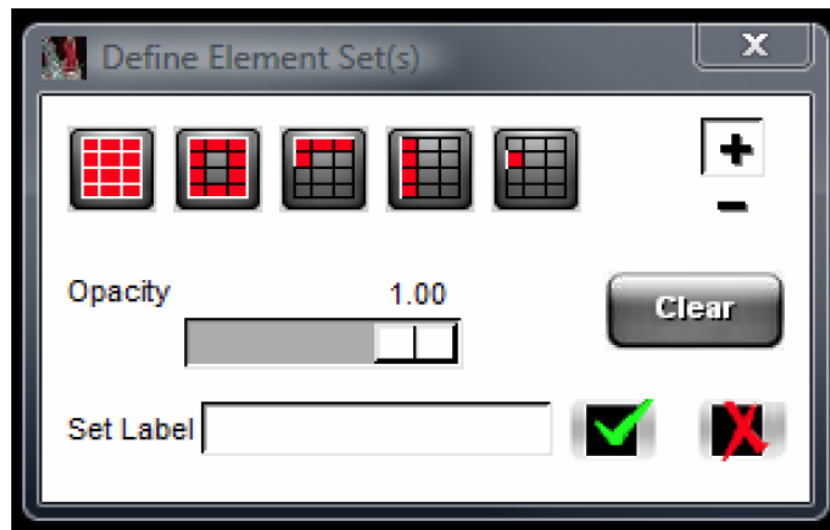
Material Properties (2)

Element Set Definition Examples

- Cortical Bone Set Definition
  1. Select the surface element button: .
  2. Hold **Ctrl button** while using the **left mouse button** to drag a rubberband box around the elements of interest
     - Selected elements will be green
  3. To accept the chosen elements, click the **right mouse button** while hovering over the mesh
     - Accepted elements will turn red
  4. **Opacity** can be modified to better visualize the data
  5. Once the selection is finalized, enter a **Set Label** (e.g. cortical bone)
  6. Click to accept the selection
- Cancellous Bone Definition
  1. Repeat the steps above except hit the button prior to accepting the element selection and assigning a new Set Label.
  2. Reduce the **opacity** to see the element set you have defined
  3. Click the button to close the Define Element Set window
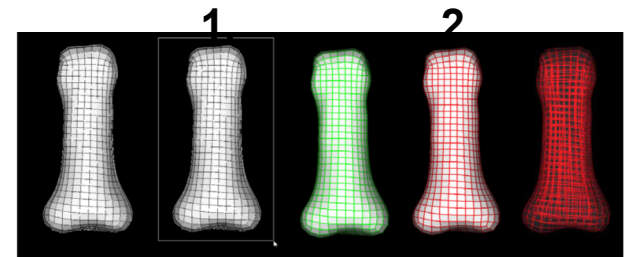
Assigning Material Properties

- Material Property Assignments
  1. Select an element set using the "Element Set" drop down menu
  2. Enter the desired **Modulus**
  3. Enter the desired **Poissson's Ratio**
  4. Click **Apply**
  5. Repeat this procedure for each material assignment
  6. Click **Cancel** to exit the operation

Assigning Material Properties

- Visualizing the Material Property Assignments

  1. Select the **Materials** tab

  2. Select **Display Material Properties** from the drop down menu

  3. Select the desired element set from the Element Set drop down menu

  4. Use the button to display a cutting plane which may be manipulated to view internal element definitions

Load and Boundary Conditions

1. Select the Load/BC tab
2. Select the STEP – Load/BC Assignments from the drop down menu
3. Select **Node Set Definitions**
4. Select ▦ from the Node Set toolbar
   - This enables the nodes associated with a face of a building block to be readily chosen
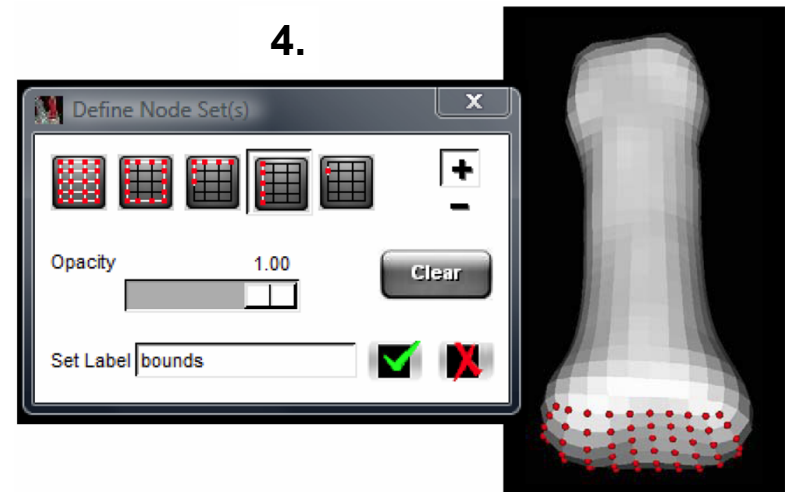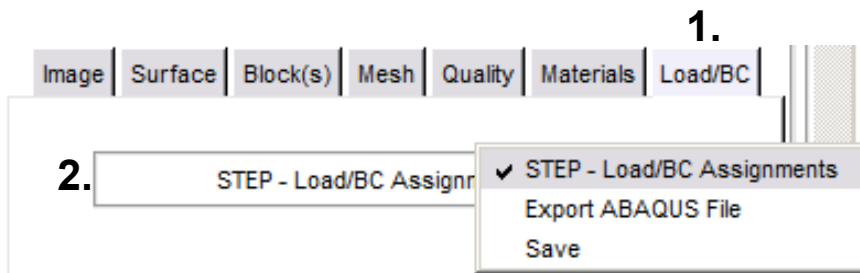
Load and Boundary Conditions (2)

5. Hold the **Ctrl button** and use the **left mouse button** to **choose a node** associated with the building block face of interest

   • Nodes associated with selected face will be highlighted in green

6. To accept the chosen nodes, click the **right mouse button** while **hovering over the mesh**

   • All nodes associated with the chosen face will turn red

   • Opacity can be changed using the slider bar

7. Once the selection is finalized, **enter a Set Label**

8. Click ✔

9. Click ✗
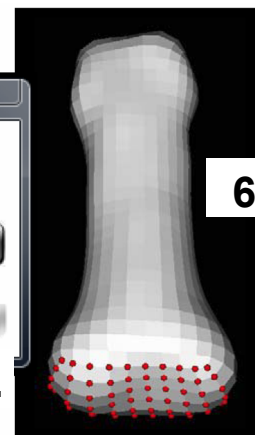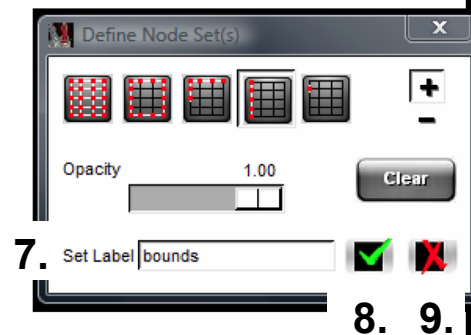
Load and Boundary Conditions (3)

10. Provide a **descriptive heading** in the Step Subheading textbox

11. Select desired **Load/Displacement** type in the drop down menu
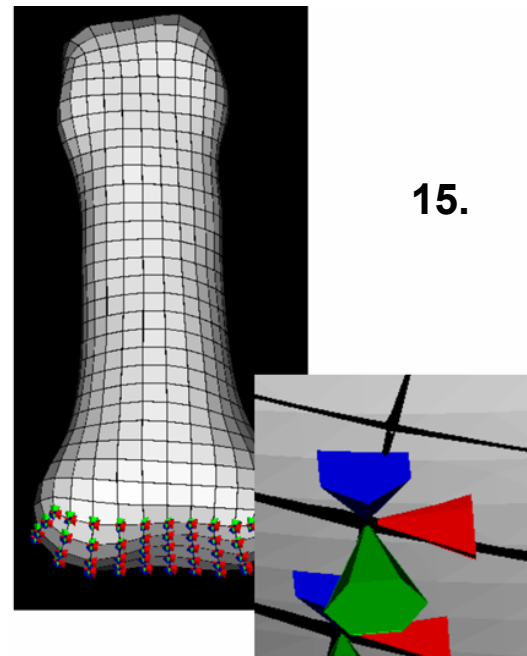
12. Select the appropriate **Node Set**
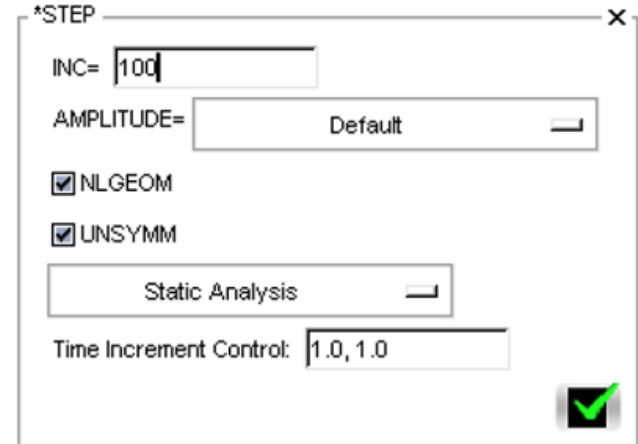
13. Assign **x, y, and z directions**

Load and Boundary Conditions (4)

14. Select Apply to update the Load/BC assignments
15. Visual confirmation will be provided on the mesh in the View Panel

15.

Assigning *STEP Definitions

1. Select the ***STEP Definitions** button

   - Please refer to the ABAQUS manual regarding these parameters

2. Use the **NSET** and **ELSET** drop down menus to select the sets of interest

3. Click **Apply** in each submenu to commit your selection
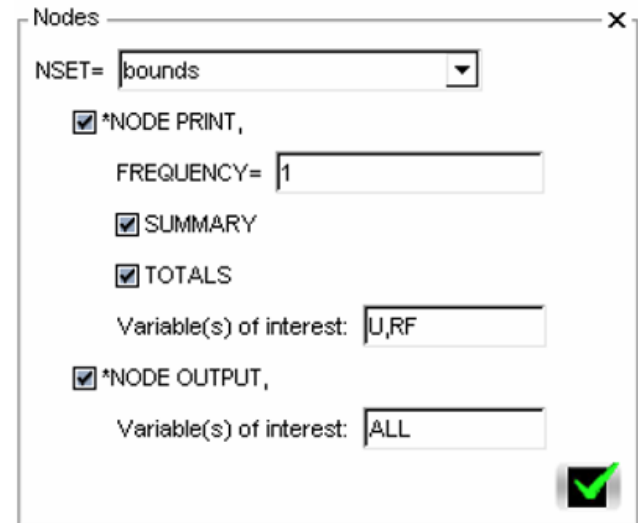
Final Steps

- Save the FE Mesh
    1. Select **Save** from the Mesh Tab
        - This can be performed at any step through the mesh development process

- Export the FE Mesh in ABAQUS file format
    1. Select **Export ABAQUS file** from the Mesh Tab
        - This can be performed at any step through the mesh development process

Review of Workflow Steps

- Input an image
- Create, smooth, (and optionally dilate) the labelmap
- Use ModelMaker to create a polygonal surface model
- Use Surface Tools to further smooth model polys using Laplacian smoothing
- Import the model into IA-FEMesh using Surface/Import Model from the MRML scene

- Create Building Blocks surrounding the surface
- Assign mesh seeds and Create the Mesh
- View the mesh quality
- Improve the mesh quality through smoothing
- Add Material Properties
- Add Initial Boundary Conditions
- Export to FE Solver (Abaqus)

Conclusion

- It is now possible to perform **end-to-end** processing from source imagery all the way through Finite Element mesh generation, mesh analysis, and mesh optimization using Slicer3

- Volumetric meshes for objects can be created through a simple, intuitive process

- Any Slicer3 model can be imported to start the mesh generation process

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