NIJ National Institute of Justice

Technology Transition Workshop | *Mohamed R. Mahfouz, Ph.D.*

Use of CT Imaging and Empirical Modeling in the Development of the Facial Reproduction Software

Outline

- Introduction
  - History
  - Problem definition
- Methods
  - Segmentation
  - Registration
  - Measurements
  - Regression model
- Results
- Conclusions
- Future

Technology
Transition Workshop

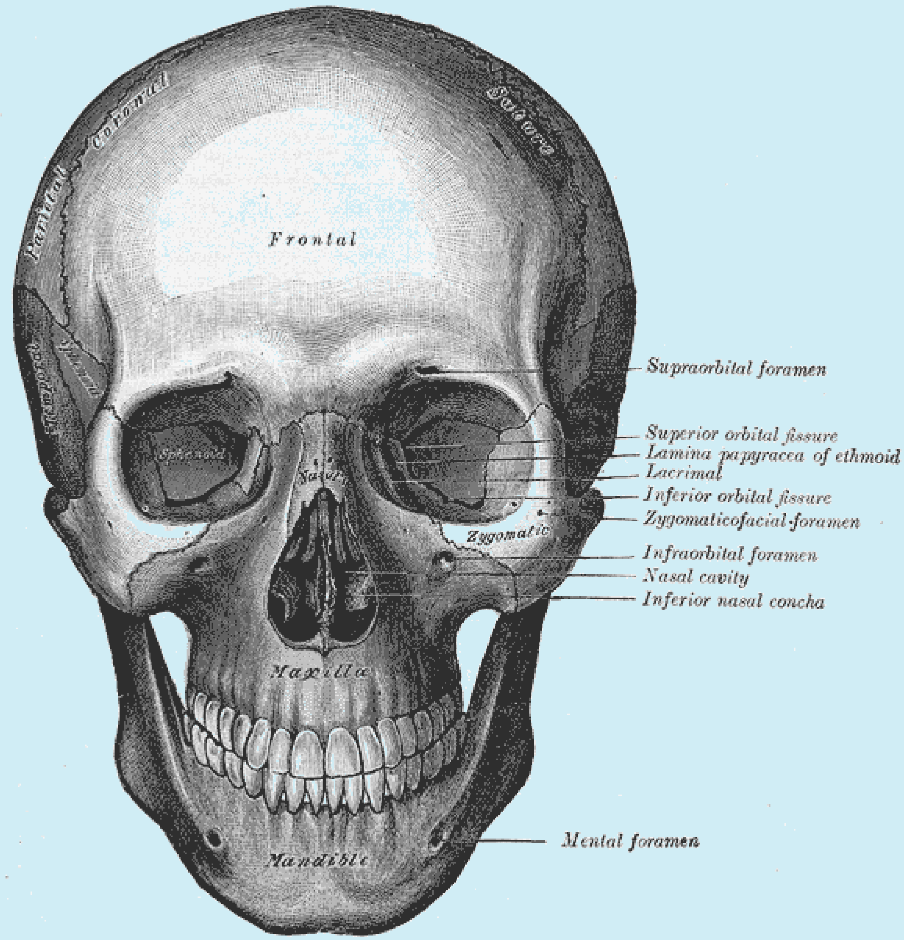
Introduction

- **Nearly all facial reproduction techniques rely on the average tissue thickness in the tables produced from past studies**
- **The average tissue thicknesses are measured at 21 traditional craniometrical landmarks on the cranium and mandible**

Technology
Transition Workshop

Introduction

#	Landmark Name
1	Supraglabella
2	Glabella
3	Nasion
4	End of Nasals
5	Mid-Philtrum
6	Upper Lip Margin
7	Lower Lip Margin
8	Chin-Lip Fold
9	Mental Eminence
10	Beneath Chin
11	Frontal Eminence
12	Supraorbital
13	Suborbital
14	Inferior Malar
15	Lateral Orbit
16	Zygomatic Arch, Midway
17	Supragleniod
18	Gonion
19	Supra M^2
20	Occlusal Line
21	Sub M^2



Traditional Locations of Fiducial Landmarks Used in Study

From Taylor (2001).

Technology Transition Workshop

Introduction

- The 21 traditional locations used on the reconstructed skull are actually a total of 32 fiducial markers because 11 of the anatomical locations are used on each side of the skull
- There are no studies of the statistical analysis of the relationship between facial and cranial landmarks and, in particular, the correlation between bone and soft-tissue landmarks around the eye orbits, nose, mouth and ears (per Vargas, Sucar and Salas, 2005)

Technology
Transition Workshop

Introduction

- **Quote from one publication discussing the issues of current facial approximation methods:**

"The intricacy and complexity of the soft tissues overlaying the skull is significant and to be able to predict them accurately and precisely from the skull alone would definitely be something special"

From Stephan (2003).

Technology Transition Workshop

NIJ National Institute of Justice

Purpose Of Study

- **Examine the possible correlations between the bony structure in the cranium and the soft tissue that surrounds it**
- **Construct an empirical model based on the correlations to predict the facial tissue depth for the 21 landmark locations**

Technology Transition Workshop

National Institute of Justice

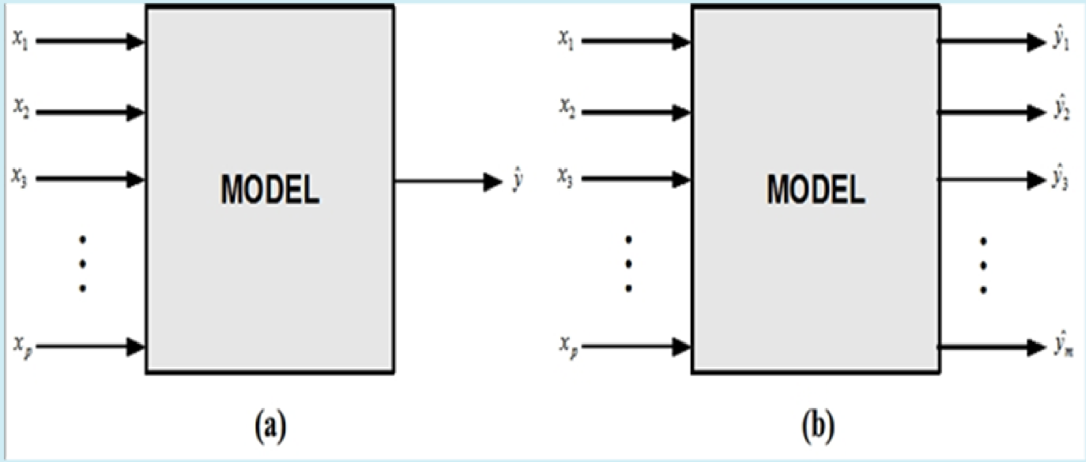
Non-Parametric Modeling

- **Uses past event data *(memory matrix)* to understand future predictions**
- **No training times**
- **Easily updated with additional data (Plug-n-Play)**
- **Three different kernel regression architectures**

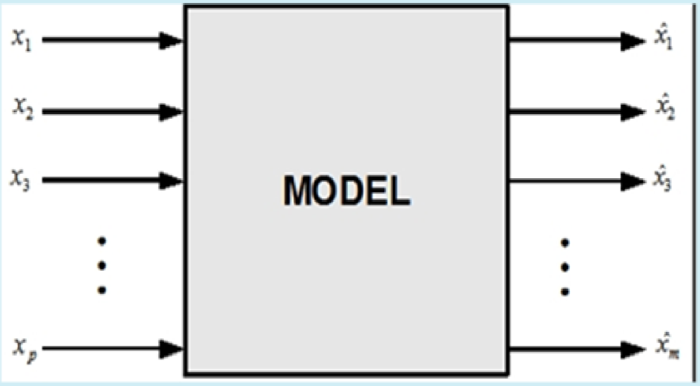
Technology Transition Workshop

NIJ National Institute of Justice

Non-Parametric Modeling



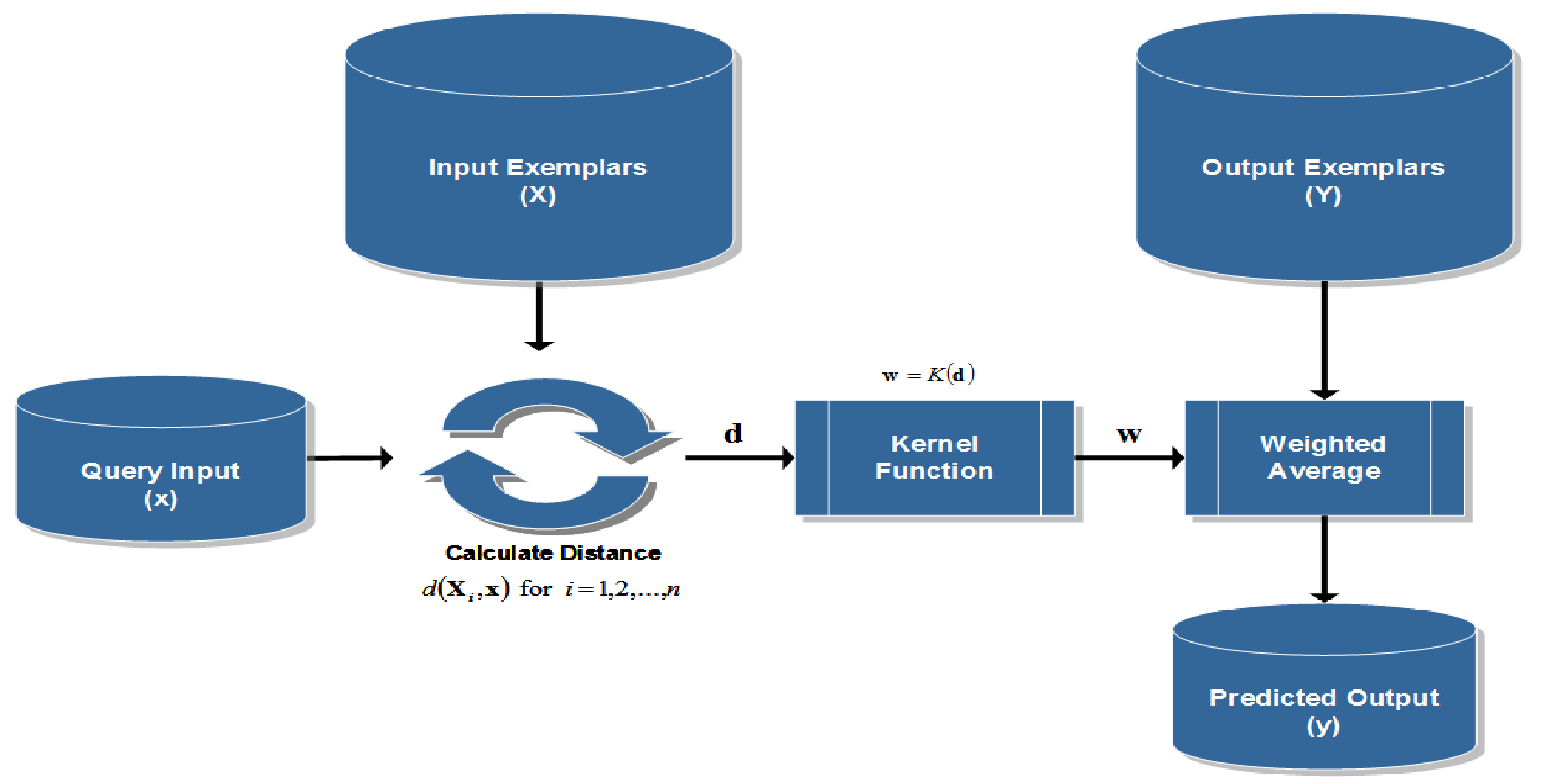
Schematic diagram of (a) inferential and (b) heteroassociative models



Schematic diagram for autoassociative model

Technology
Transition Workshop

Non-Parametric Modeling



Technology
Transition Workshop

Non-Parametric Modeling

- **Euclidean distance**

$$d(x_i, q) = \sqrt{\sum_{i=1}^{n} \left(x_q^i - m_j^i\right)^2}$$

- **Gaussian Kernel**

$$w = K(d, h) = \frac{1}{\sqrt{2\pi \cdot h^2}} e^{-d^2 / 2h^2}$$

- **Prediction**

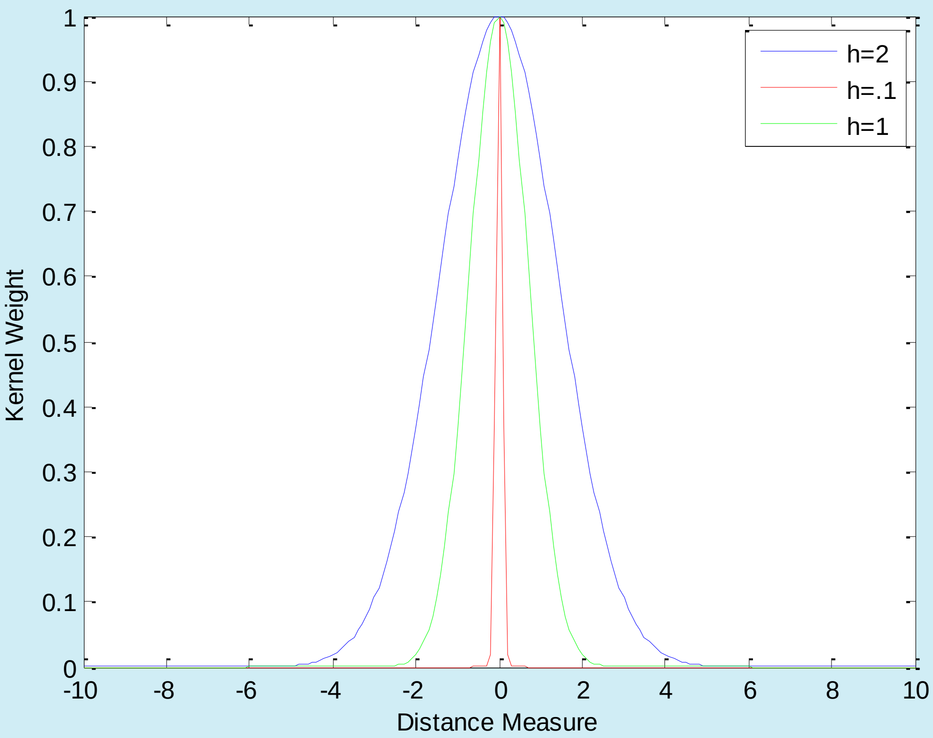
$$\hat{y}(q) = \frac{\sum_{i=1:n} y_i w_i}{\sum_{i=1:n} w_i} = \frac{\sum_{i=1:n} y_i K(d(x_i, q))}{\sum_{i=1:n} K(d(x_i, q))}$$

Technology
Transition Workshop

National Institute of Justice

Non-Parametric Modeling

- **Gaussian Kernel**
- **Varying bandwidths (h)**
- **Optimizing to reduce MSE of predictions**



Technology
Transition Workshop

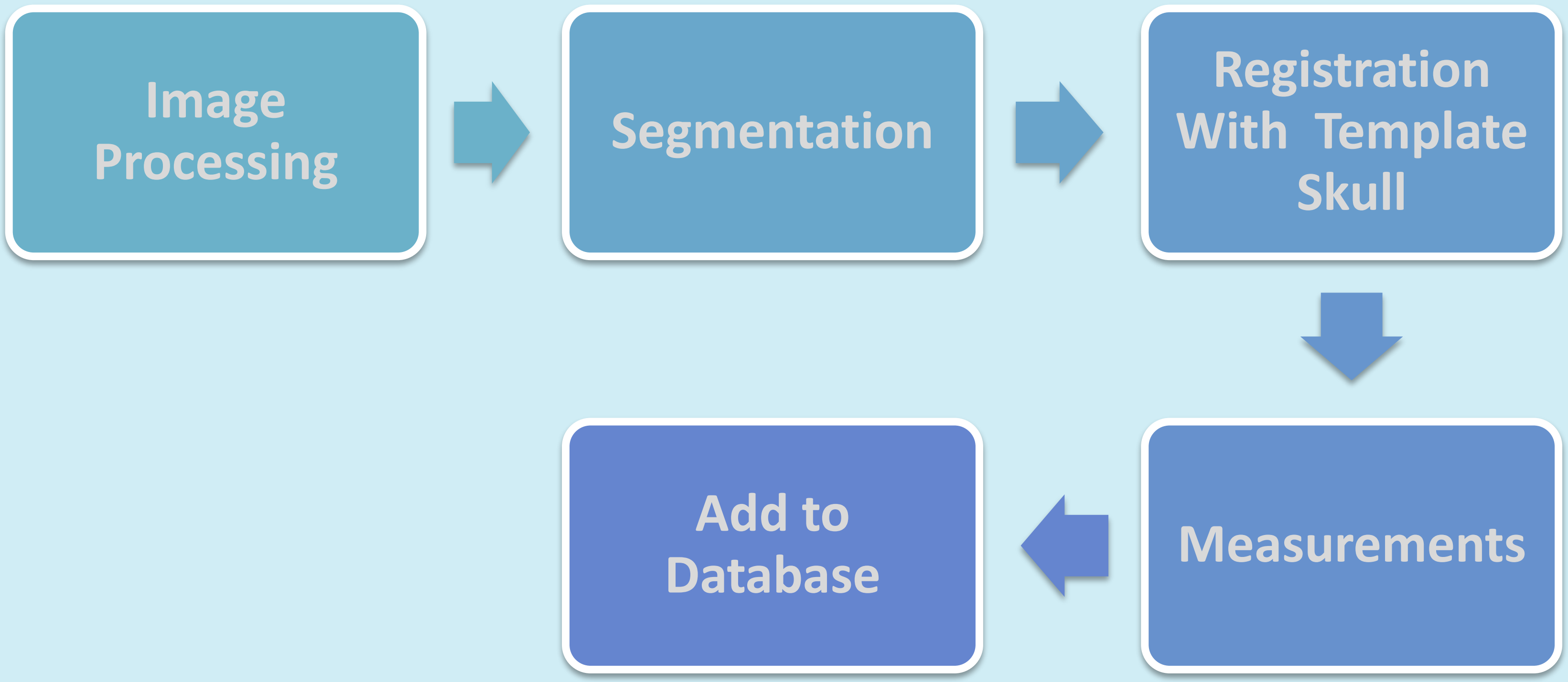
Methods

- **CT Image Collection:**
  - **100 male subjects**
  - **CT data was collected in the PET/CT Imaging Department of Thompson Cancer Survival Center West in Knoxville, Tennessee**
  - **Only those with PET/CT scans labeled as melanoma, bone, and brain were examined as possible subjects to use in the study because their scan procedures should have included the complete cranium and mandible**

Technology Transition Workshop

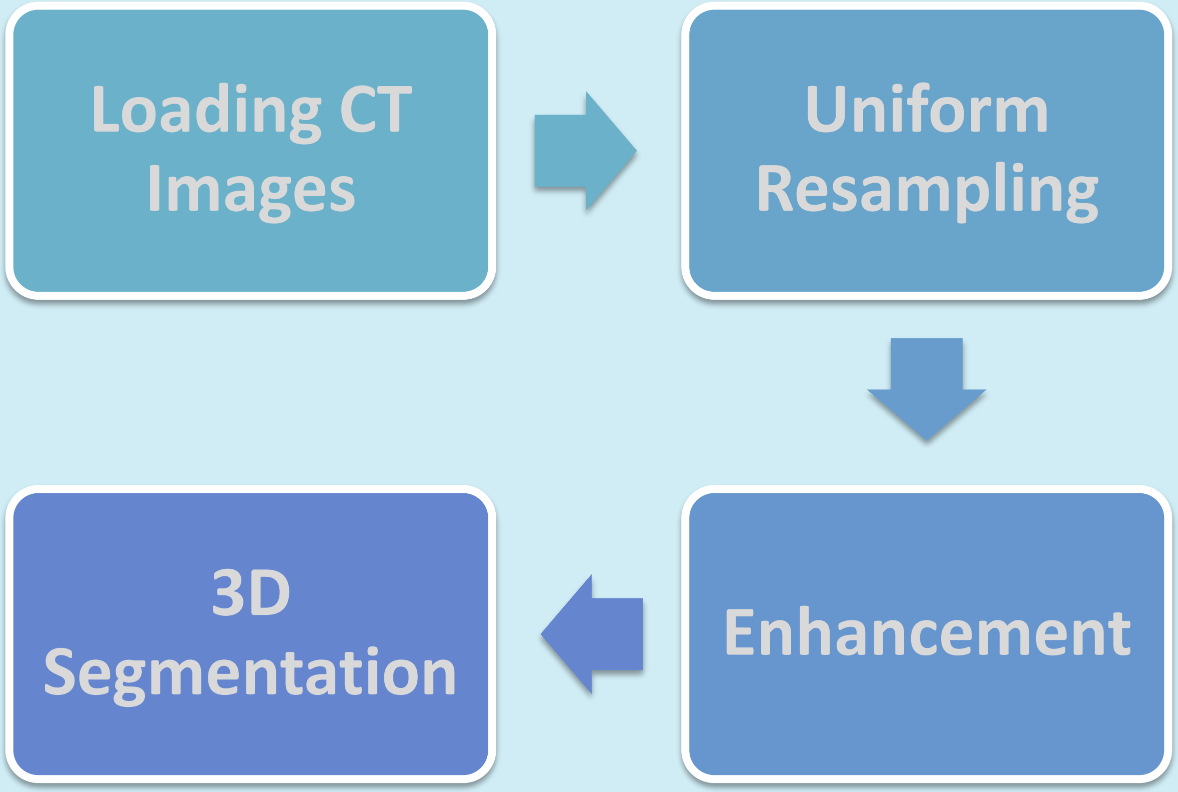
NIJ National Institute of Justice

Methods



Technology Transition Workshop

Methods (Processing and Segmentation)



Technology
Transition Workshop

Uniform Resampling

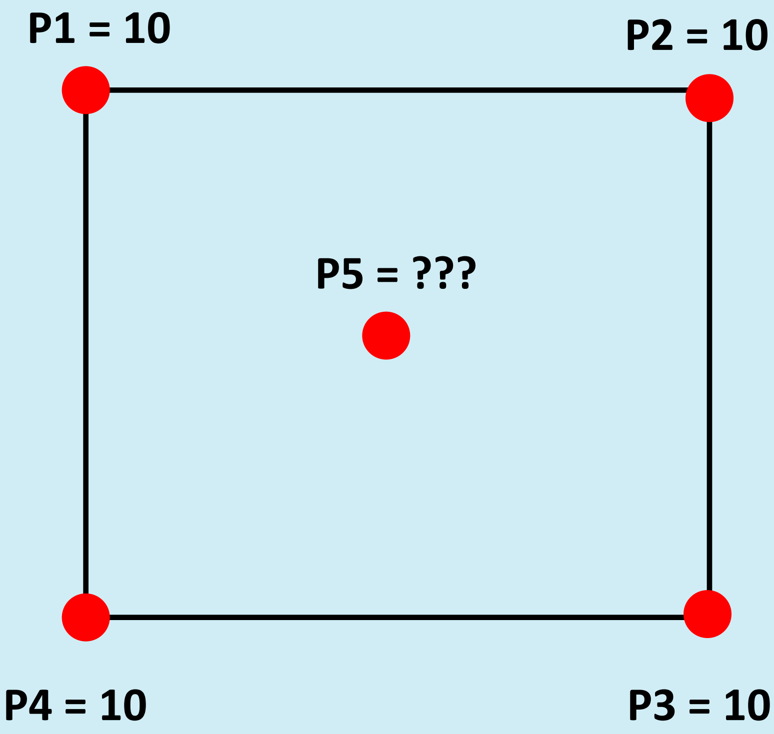
- Use when slices are not equally spaced or there is a large gap between each slice
- Uniform resampling :
  - Stacks the images in a volume data
  - Re-slice the volume with equidistance planes
  - Fill the gaps between each slice using interpolation
- The output volume has better resolution and can be segmented easily

Technology
Transition Workshop

NIJ National Institute of Justice

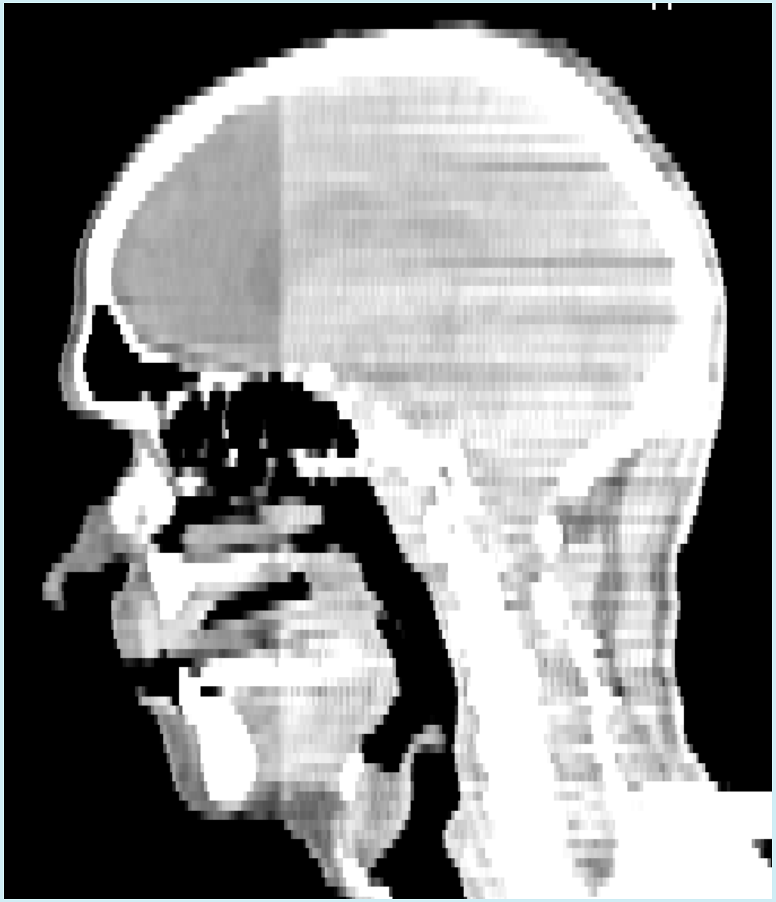
Interpolation

- Interpolation: compute data from known points
- Given P1, P2 , P3 and P4, what is the value of p5?
- Different types of Interpolation:
  - Nearest neighbor
  - Linear
  - Bilinear
  - Cubic

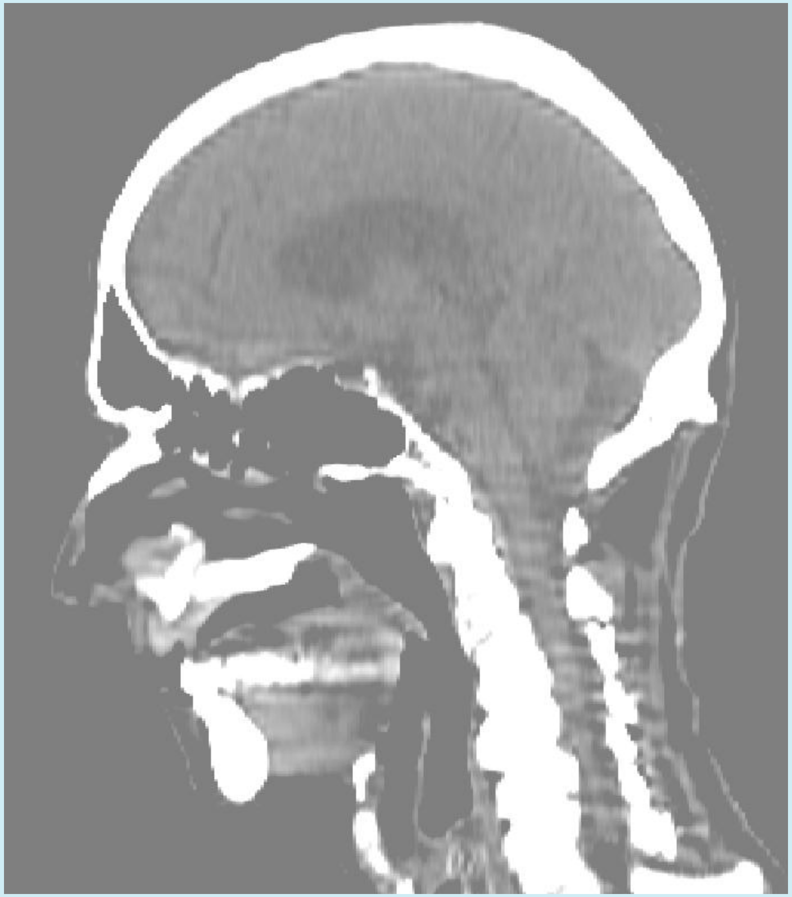


Technology Transition Workshop

Uniform Resampling



Before Resampling

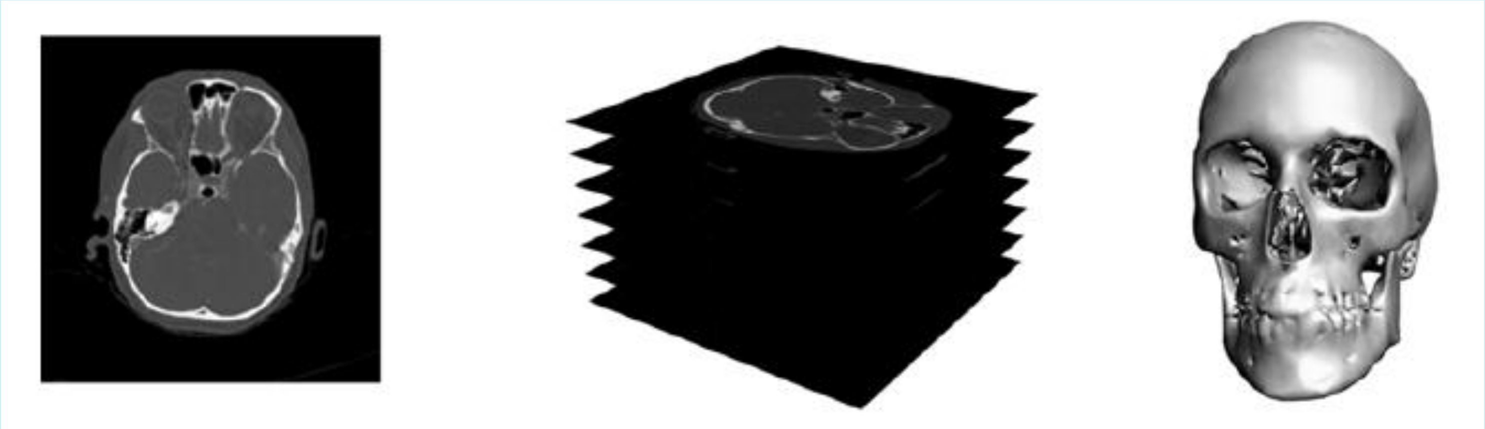


After Resampling

Technology Transition Workshop

NIJ National Institute of Justice

Segmentation



DICOM Slice to 3D Surface Model

Technology
Transition Workshop

NIJ National Institute of Justice

CT Volume Segmentation

- **Extract bone contour from each CT slice to construct surface model from volume**
- **Data Window and Threshold settings**
    - **150 to 255**
- **Scattering problems**
- **Smoothing to 100,000 faces**
- **Procedure developed for consistent segmenting of all 100 skulls**
- **Allows for surface to surface registration**

Technology Transition Workshop

NIJ National Institute of Justice

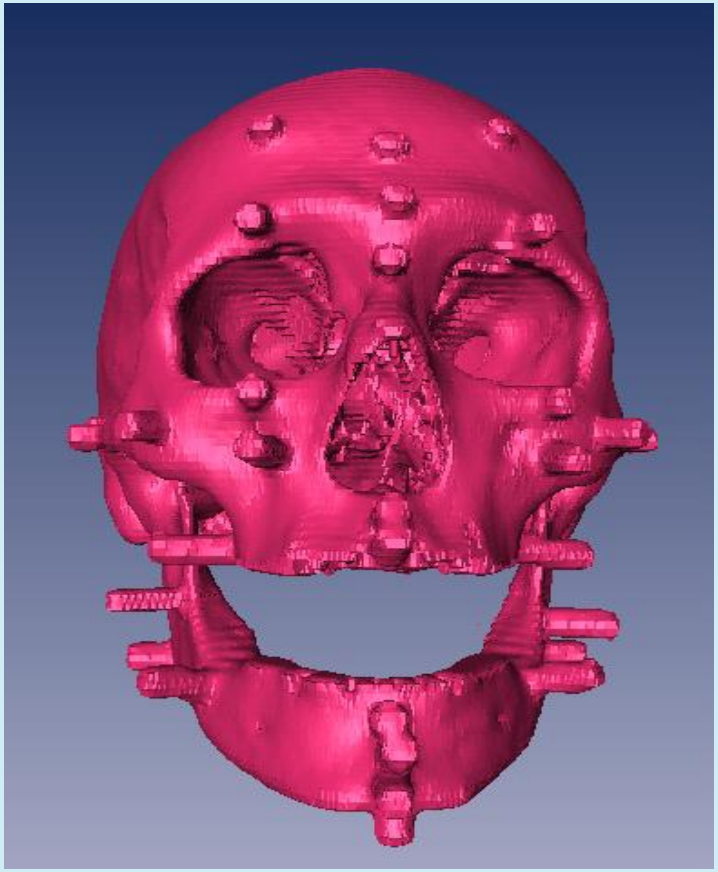
3D-3D Registration

- **Surface to surface registration**
- **Skull from Anthropology used as base model**
  - **Purpose: to locate the correct locations for tissue measurement on each skull in the database**

Technology
Transition Workshop

NIJ National Institute of Justice

Template Skull

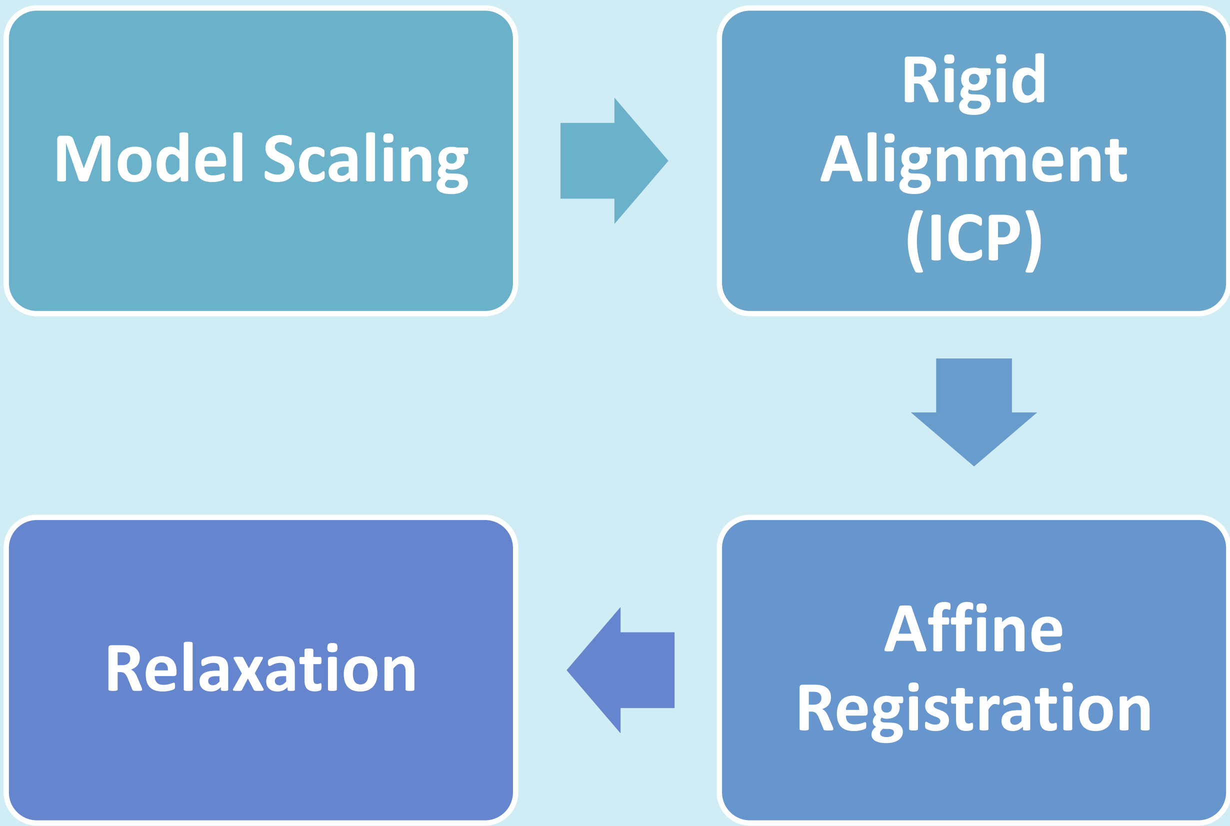


Segmented Base Skull With the 32 Fiducial Markers

Technology Transition Workshop

NIJ National Institute of Justice

3D-3D Registration



Technology
Transition Workshop

NIJ
National Institute of Justice

Iterative Closest Point (ICP)

- **Uses closest point pairs on two different meshes to compute least squares transformation that best aligns meshes**

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & t_x \\ a_{21} & a_{22} & a_{23} & t_y \\ a_{31} & a_{32} & a_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Technology
Transition Workshop

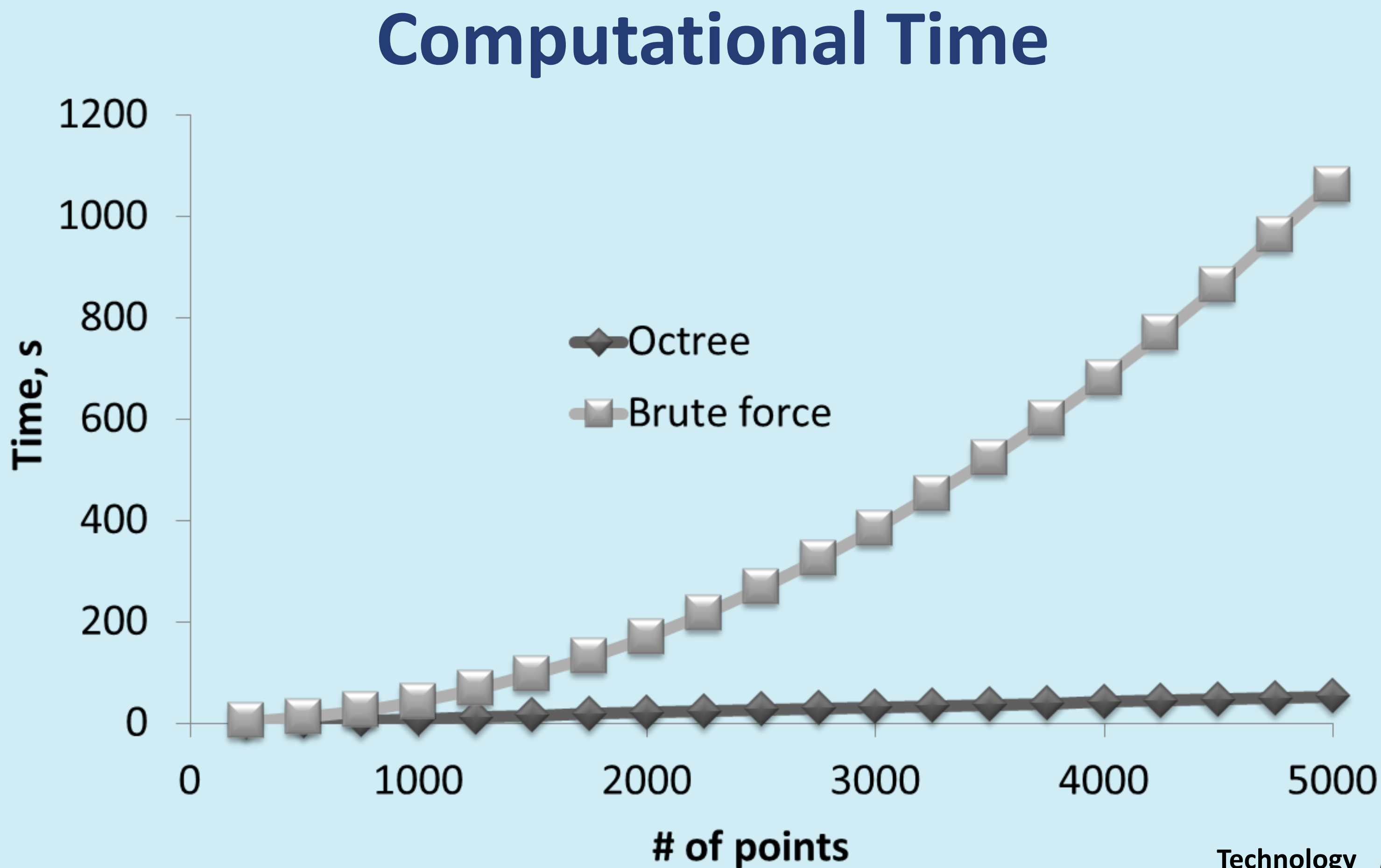
Octree-based ICP

- Exhaustively searching both meshes for closest point is inefficient
- Octree provides reduced search domain
- O(N Log (N)) vs. O(N2) complexity

Technology
Transition Workshop

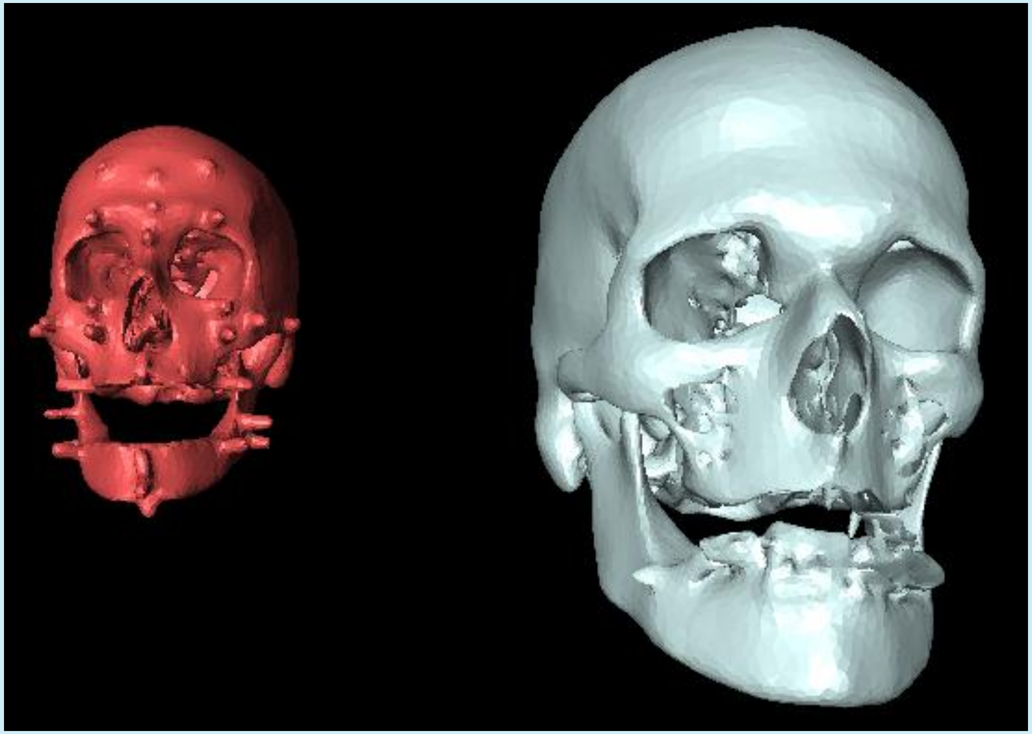
NIJ National Institute of Justice

Octree vs. Brute Force



Technology
Transition Workshop

Alignment Using ICP



Before Alignment

After Alignment

Technology
Transition Workshop

NIJ National Institute of Justice

Affine Registration

- Affine registration [T] maps one model [A] to another model [B] by finding:
  - Translation
  - Rotation
  - Scale or shear

$$B = T * A$$

- Using Octree find closest points between new skull and base skull

Technology
Transition Workshop

NIJ National Institute of Justice

Affine Registration

Before Affine Registration

After Affine Registration

Technology
Transition Workshop

NIJ National Institute of Justice

Relaxation

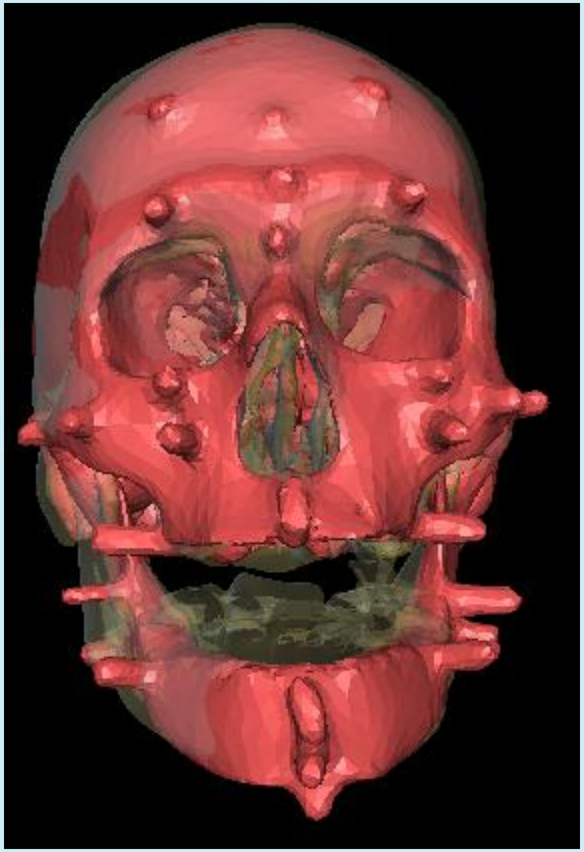
- Affine registration is rigid (apply same transformation on all model points)
- Relaxation is a free form deformation where each point on the base skull is allowed to move freely to the nearest point on the new skull

Technology
Transition Workshop

NIJ National Institute of Justice

Relaxation

Before Relaxation

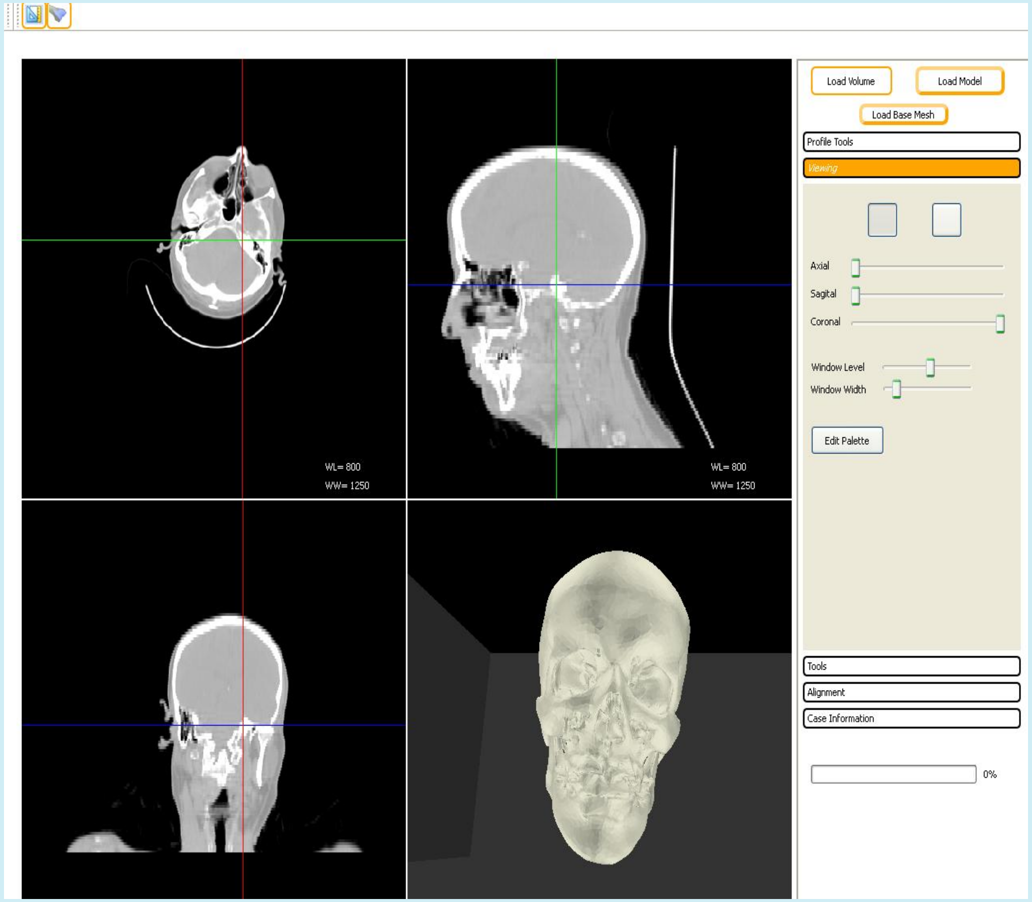


After Relaxation

Technology
Transition Workshop

NIJ National Institute of Justice

3D-3D Registration

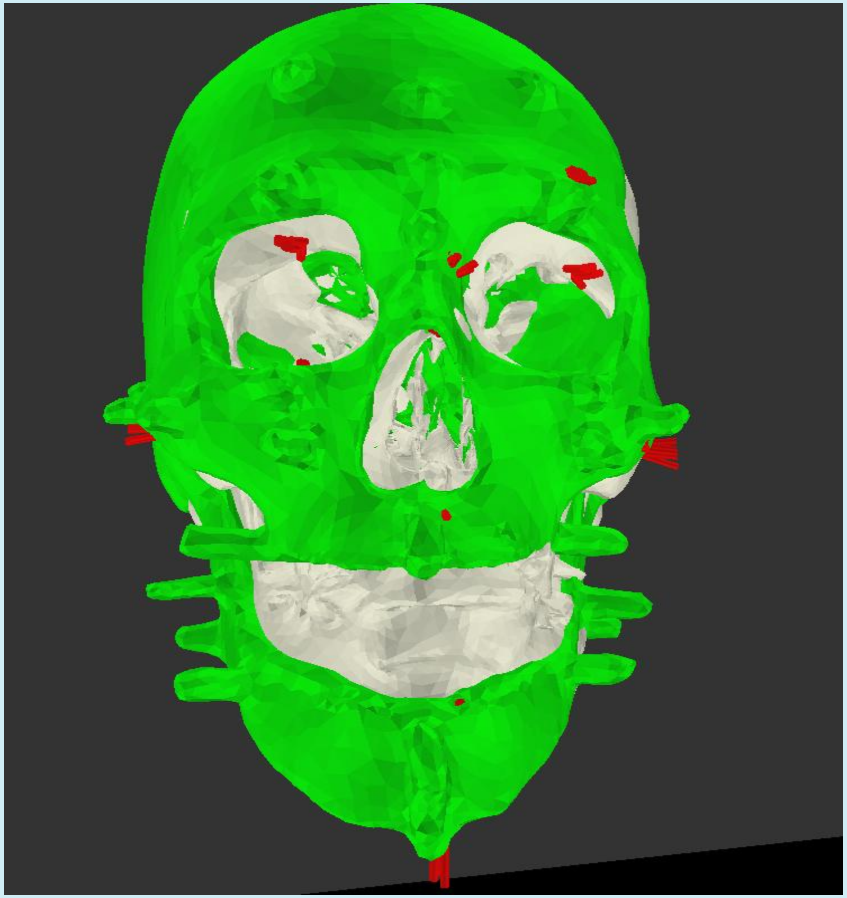


Software Home Screen With Subject Volume and Model Loaded

Technology Transition Workshop

NIJ National Institute of Justice

3D-3D Registration



Registered Base Model
And New Model in IMF

Technology
Transition Workshop
NIJ National Institute of Justice

Tissue and Bone Thickness Measurements

- One skull at a time
- Picked 30-40 points at desired craniometrical location
- Tissue and bone thickness measured for each point selected

Technology
Transition Workshop

NIJ National Institute of Justice

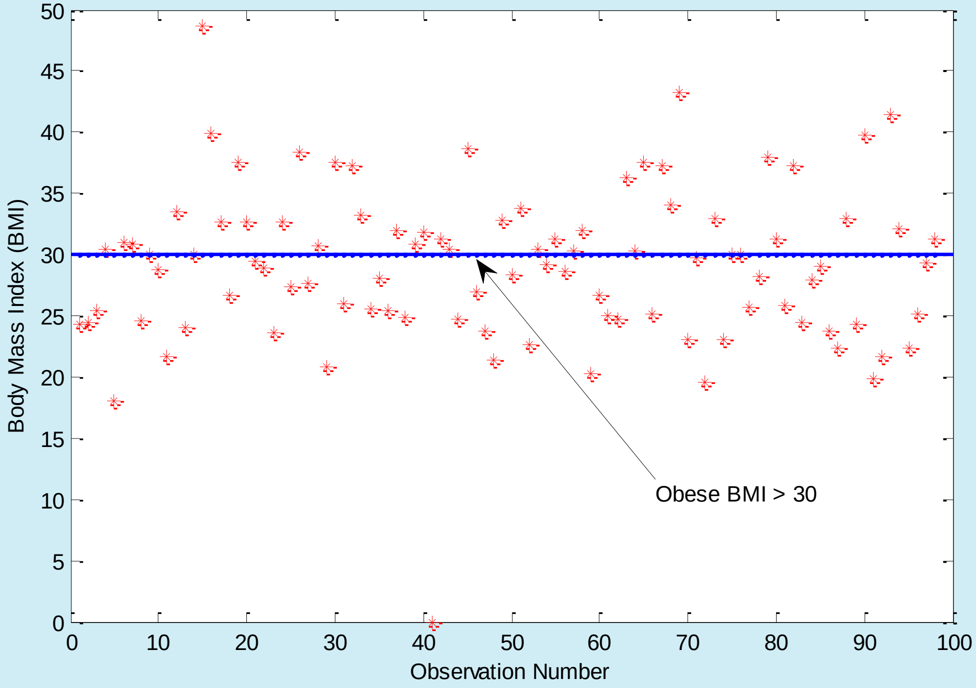
Tissue and Bone Thickness Measurements

- **13 Landmarks used for bone thickness measurements**
- **Limitation due to database BMI and age**
- **Useful landmarks mainly along the midline of the skull and forehead**
  - **Due to lack of suitability of landmarks on areas of skull with skin sagging from aging and obesity being prominent**

Technology
Transition Workshop

BMI

- **Average BMI for Subjects:**
  - **29.0449 kg/m²**



Technology Transition Workshop

List of Landmarks Used for Bone Thickness

#	Landmark Name
1	Supraglabella (1)
2	Glabella (2)
3	Nasion (3)
4	End of Nasals (4)
5	Mid-Philtrum (5)
6	Chin-Lip Fold (8)
7	Mental Eminence (9)
8	Beneath Chin (10)
9	Frontal Eminence (11)
10	Supraorbital (12)
11	Suborbital (13)
12	Lateral Orbit (15)
13	Zygomatic Arch, Midway (16)

Technology
Transition Workshop

NIJ National Institute of Justice

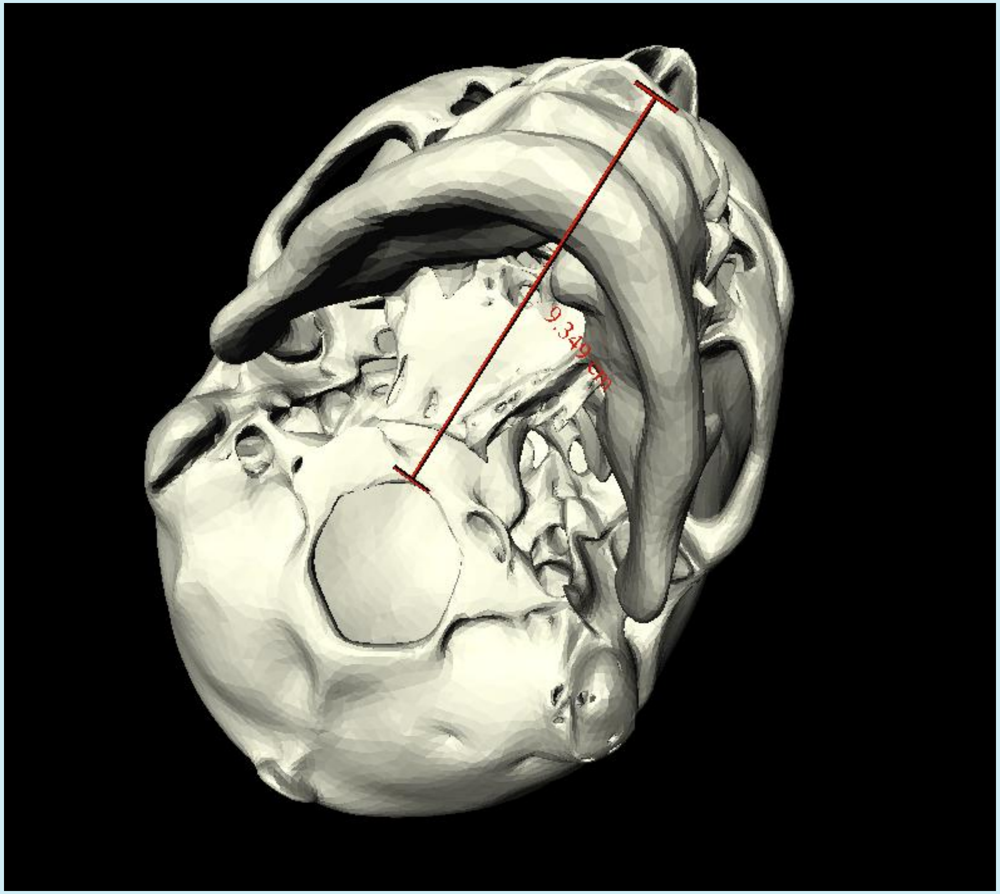
Ethnicity Determination

- **5 selected distance measurements**
  - **Basion-Prosthion**
  - **Basion-Nasion**
  - **Orbit height**
  - **Nasal breadth**
  - **Biauricular breadth**
- **Conducted on segmented surface models**

Technology Transition Workshop

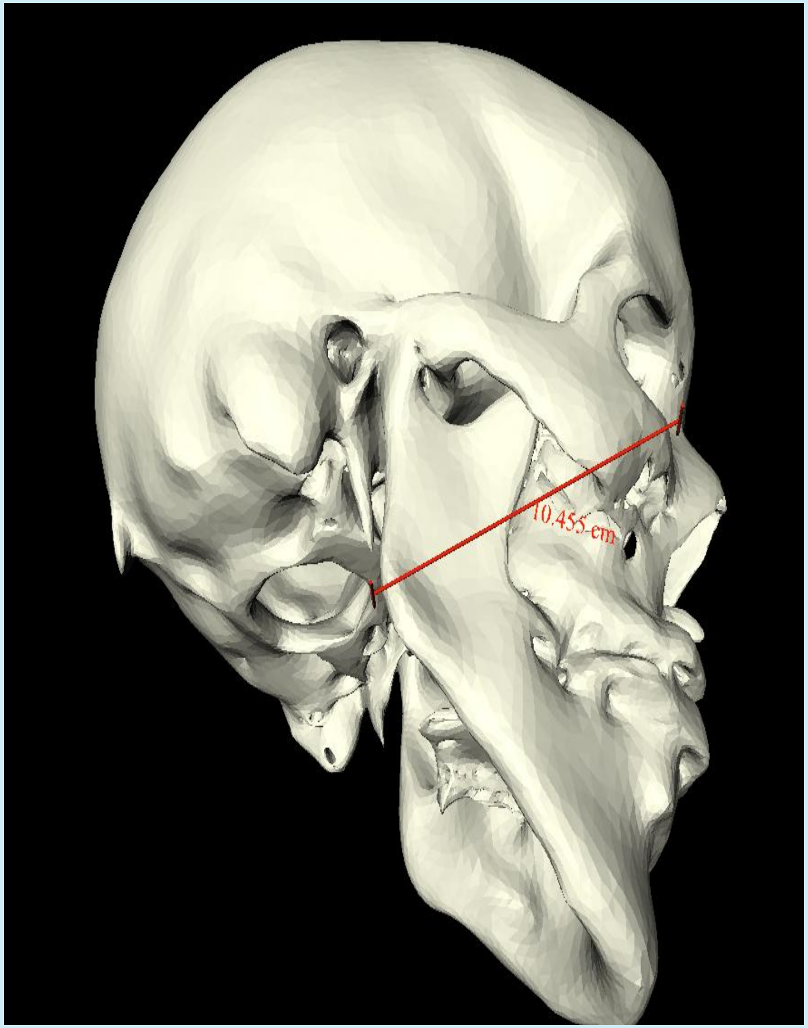
NIJ National Institute of Justice

Basion-Prosthion



Technology
Transition Workshop

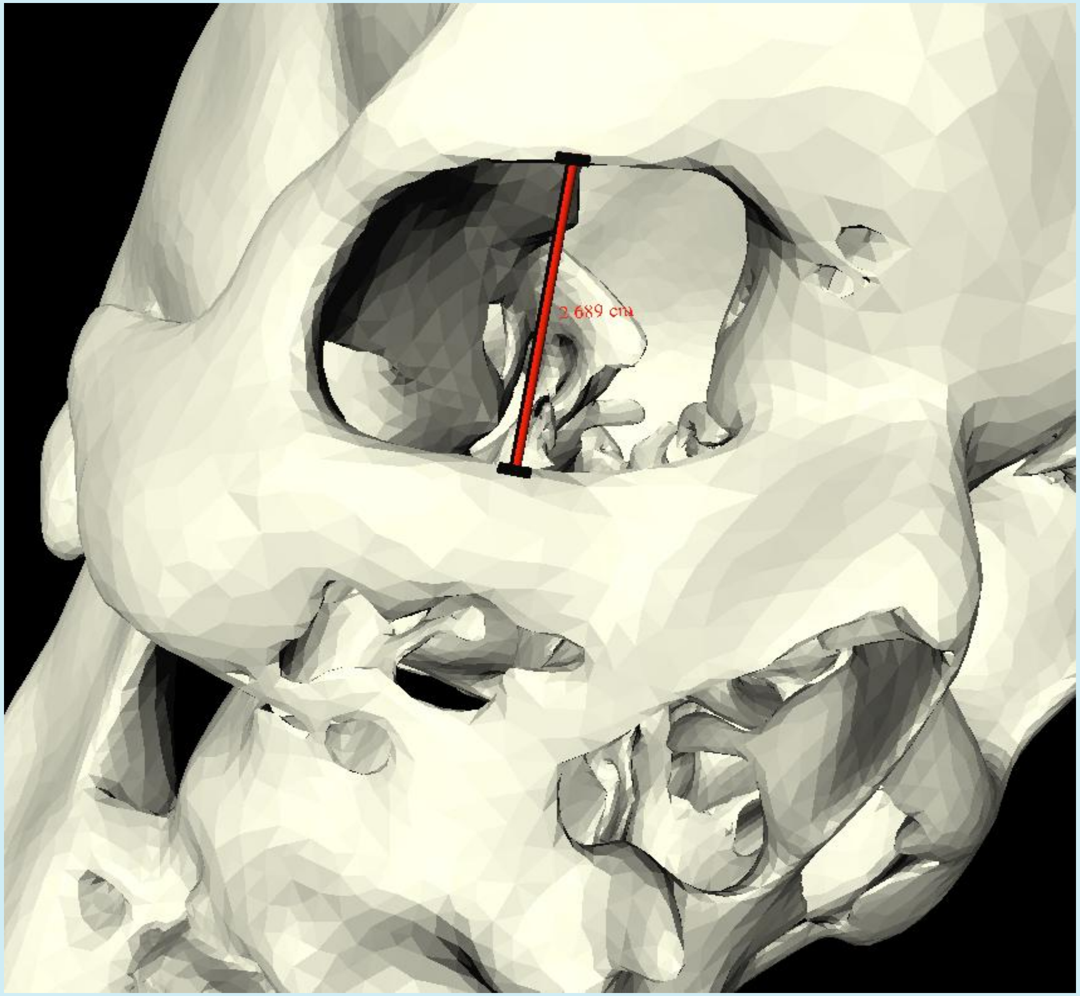
Basion-Nasion



Technology
Transition Workshop

NIJ National Institute of Justice

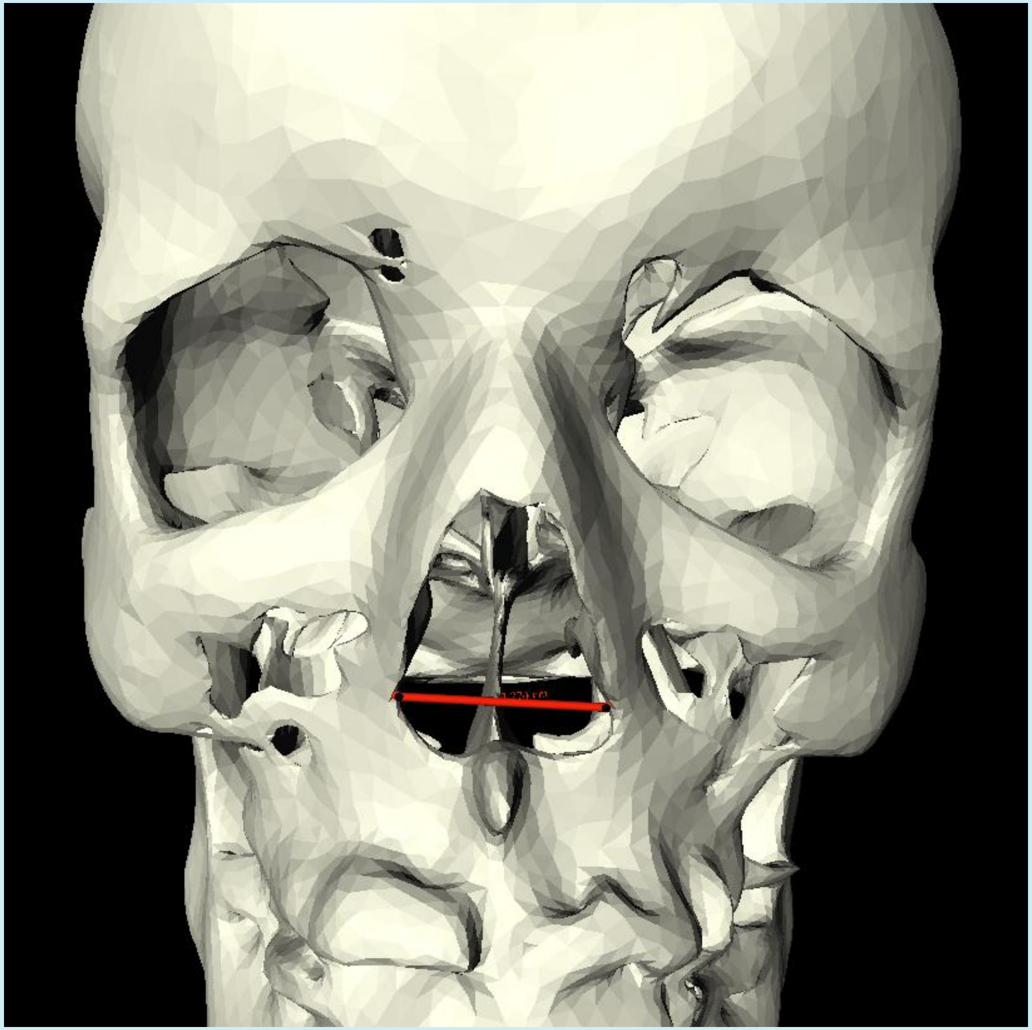
Orbit Height



Technology
Transition Workshop

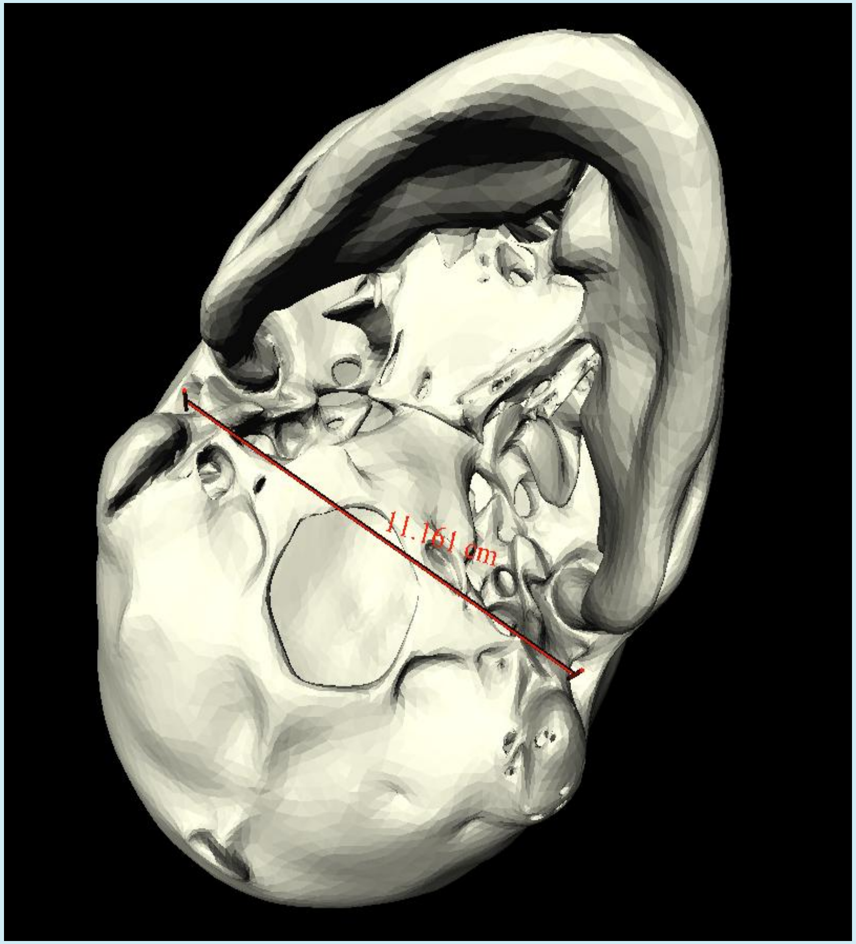
NIJ National Institute of Justice

Nasal Breadth



Technology
Transition Workshop

Biauricular Breadth



Technology
Transition Workshop

Kernel Regression Estimation

- **Input Memory Matrix:**
  - **100 observations**
  - **22 variables:**
    - **13 bone thickness measurements**
    - **5 ethnicity determination measurements**
    - **4 demographics:**
      - **Age**
      - **Weight**
      - **Height**
      - **BMI**
- **Output Memory Matrix:**
  - **13 facial tissue thicknesses**

#	Landmark Name
1	Supraglabella (1)
2	Glabella (2)
3	Nasion (3)
4	End of Nasals (4)
5	Mid-Philtrum (5)
6	Chin-Lip Fold (8)
7	Mental Eminence (9)
8	Beneath Chin (10)
9	Frontal Eminence (11)
10	Supraorbital (12)
11	Suborbital (13)
12	Lateral Orbit (15)
13	Zygomatic Arch, Midway (16)

Technology
Transition Workshop

NIJ National Institute of Justice

HAKR Model

Input Exemplars

$$\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Query Input

$$\begin{bmatrix} q_1 & q_n & \cdots & q_n \end{bmatrix}$$

Weights

$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix}$$

<u>Exemplar Matrix sizes</u>

n – Variables, m – Observations (~100)

Output Exemplars

$$\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix}$$

Output (y)

$$\begin{bmatrix} y_1 & y_n & \cdots & y_n \end{bmatrix}$$

Technology Transition Workshop

NIJ National Institute of Justice

Inferential KR Model

Input Exemplars

$$\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Query Input

$$[q_1 \quad q_n \quad \cdots \quad q_n]$$

Weights

$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix}$$

Exemplar Matrix sizes

n – Variables, m – Observations (~100)

Output Exemplar

$$\begin{bmatrix} y_{11} \\ y_{21} \\ \vdots \\ y_{m1} \end{bmatrix} \; \mathbf{X} \; \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix}$$

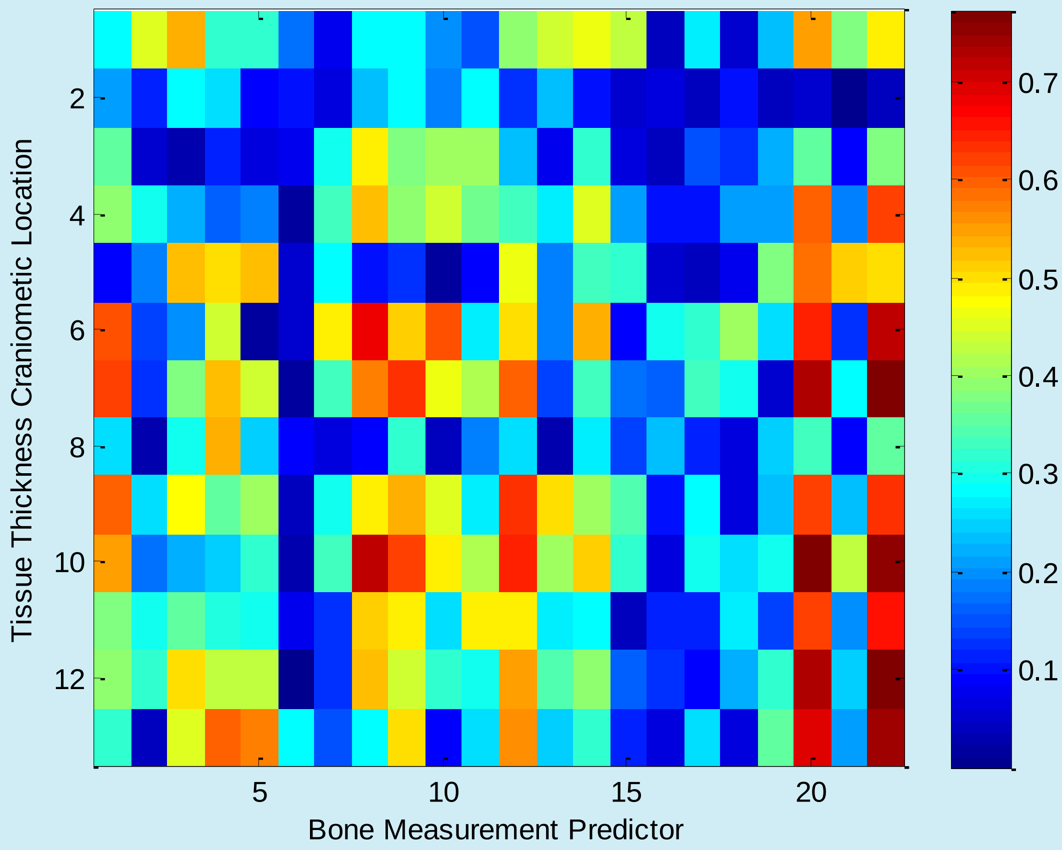
Output (y)

$$[y_n]$$

Technology
Transition Workshop

Correlation Analysis

- **Linear correlation**
- **Abs values of 0.3 or greater are useful**
- **Very high correlations in the weight (20) and BMI (22) predictors**



Technology Transition Workshop

NIJ National Institute of Justice

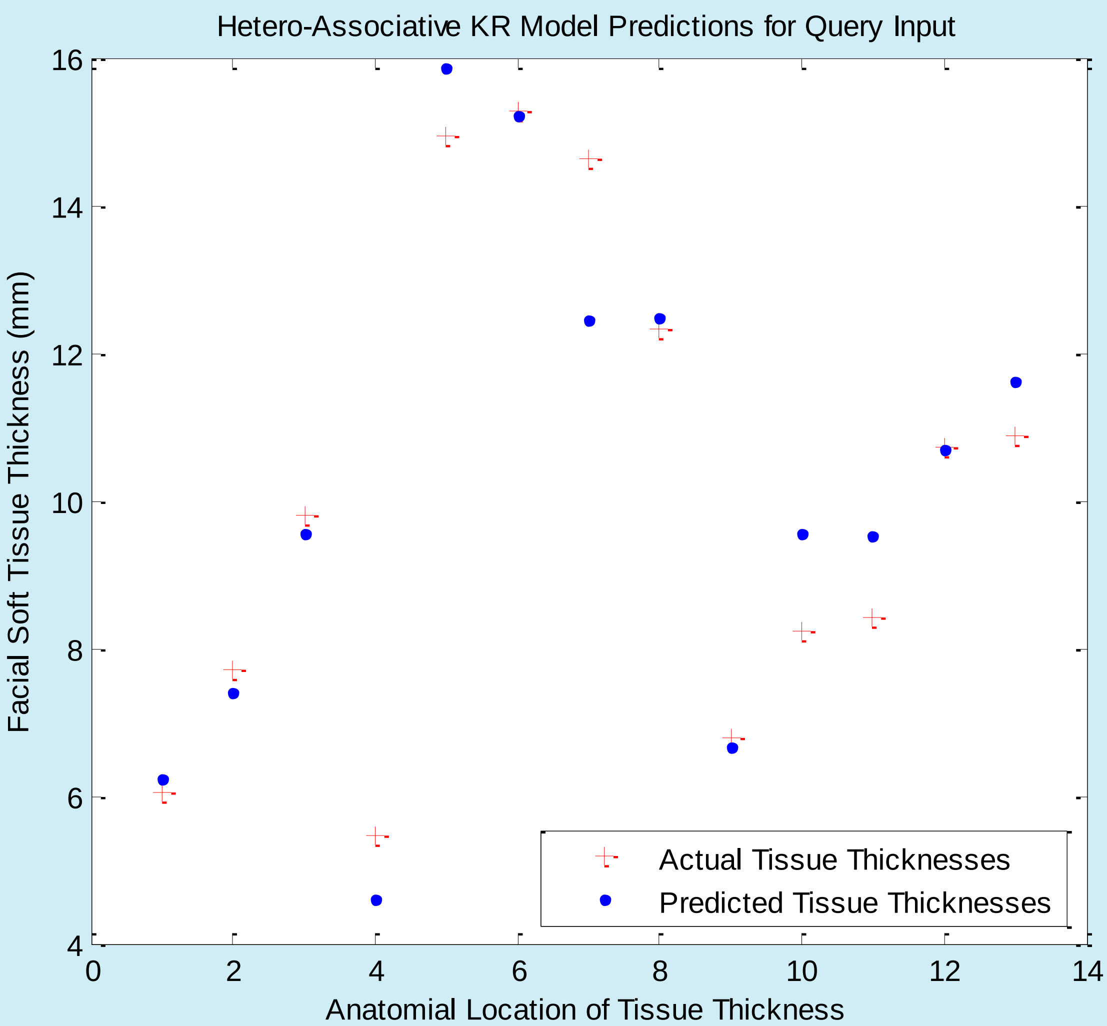
Correlation Analysis

	Supraglabella	Glabella	Nasion	End of Nasals	Mid-Philtrum	Chin-Lip Fold	Mental Eminence	Beneath Chin	Frontal Eminence	Supraorbital	Suborbital	Lateral Orbit	Zygomatic Arch
Supraglabella	0.03	0.08	0.09	0.17	0.03	0.21	0.19	0.06	0.15	0.14	0.09	0.00	0.09
Glabella	-0.11	0.09	-0.02	-0.08	-0.02	0.02	0.00	-0.05	-0.05	0.04	-0.11	-0.22	-0.02
Nasion	-0.04	0.07	0.04	-0.21	-0.08	-0.08	-0.12	-0.04	-0.08	0.02	-0.04	-0.13	-0.04
End of Nasals	0.08	0.05	0.00	-0.06	-0.14	-0.04	-0.21	-0.15	0.02	-0.01	0.11	0.05	-0.02
Mid-Philtrum	-0.11	0.06	0.08	-0.19	-0.22	0.05	-0.14	-0.16	-0.19	-0.08	-0.10	-0.17	-0.25
Chin-Lip Fold	-0.16	-0.16	-0.10	-0.04	0.08	-0.20	-0.18	-0.01	-0.13	-0.09	-0.07	-0.15	-0.04
Mental Eminence	0.08	-0.06	-0.03	0.06	-0.07	0.06	-0.04	-0.02	0.14	0.13	0.05	0.04	-0.08
Beneath Chin	0.32	0.20	0.12	0.26	0.12	0.31	0.30	0.17	**0.41**	**0.38**	**0.30**	**0.36**	0.26
Frontal Eminence	0.10	0.13	0.14	0.26	0.01	0.19	0.26	0.18	0.22	0.27	0.17	0.16	0.20
Supraorbital	0.11	0.09	0.12	0.15	0.02	0.24	0.20	-0.02	0.24	0.19	0.14	0.14	-0.01
Suborbital	-0.20	-0.03	-0.11	-0.26	0.08	-0.13	-0.10	-0.12	-0.24	-0.18	0.04	-0.05	-0.12
Lateral Orbit	0.13	0.05	0.05	0.18	0.12	0.14	0.09	0.06	0.24	0.23	0.13	0.00	0.20
Zygomatic Arch	-0.15	0.01	0.18	-0.16	-0.05	-0.09	-0.13	-0.17	-0.19	-0.10	-0.08	-0.16	-0.16
Basion to Prosthion distance	**0.32**	0.19	0.27	0.27	-0.12	0.32	0.17	0.08	0.34	0.25	0.04	0.21	0.26
Basion to Nasion distance	0.26	0.10	0.02	0.15	0.02	0.07	0.11	0.04	0.28	0.12	0.02	0.13	0.09
Orbital width	-0.20	-0.16	-0.23	-0.18	-0.03	-0.24	-0.14	-0.29	-0.19	-0.22	-0.14	-0.26	-0.18
Nasal width	0.00	-0.11	-0.16	-0.05	-0.06	-0.07	0.01	-0.09	-0.03	-0.01	-0.06	-0.12	-0.10
Biauricular breadth	-0.09	-0.15	-0.12	0.03	0.12	0.00	-0.01	-0.03	-0.16	-0.19	0.06	-0.02	-0.08
Age	-0.29	-0.21	-0.25	-0.15	-0.28	-0.21	-0.13	-0.28	-0.26	-0.27	-0.08	-0.20	-**0.40**
Weight	**0.65**	**0.44**	**0.36**	**0.37**	**0.33**	**0.57**	**0.55**	**0.49**	**0.64**	**0.64**	**0.59**	**0.67**	**0.72**
Height	0.19	0.09	0.15	0.08	-0.04	0.23	0.11	0.03	0.17	0.11	0.03	0.12	0.21
BMI	**0.58**	**0.42**	**0.38**	**0.36**	0.27	**0.60**	**0.58**	**0.44**	**0.57**	**0.59**	**0.56**	**0.64**	**0.73**

NIJ National Institute of Justice

Correlation Matrix of Model Predictors and Responses From 100 Skulls

HAKR Model Results



- LOOCV performed
- 4 performance metrics
- 3 different RMSEs and a prediction reliability

Technology Transition Workshop

NIJ National Institute of Justice

HAKR Model Results

Prediction Uncertainty	Model RMSE	Table RMSE	Similarity
19.73 %	2.04 mm	3.07 mm	0.19

Average Performance Metrics for All HAKR Models Using Demographic Predictors

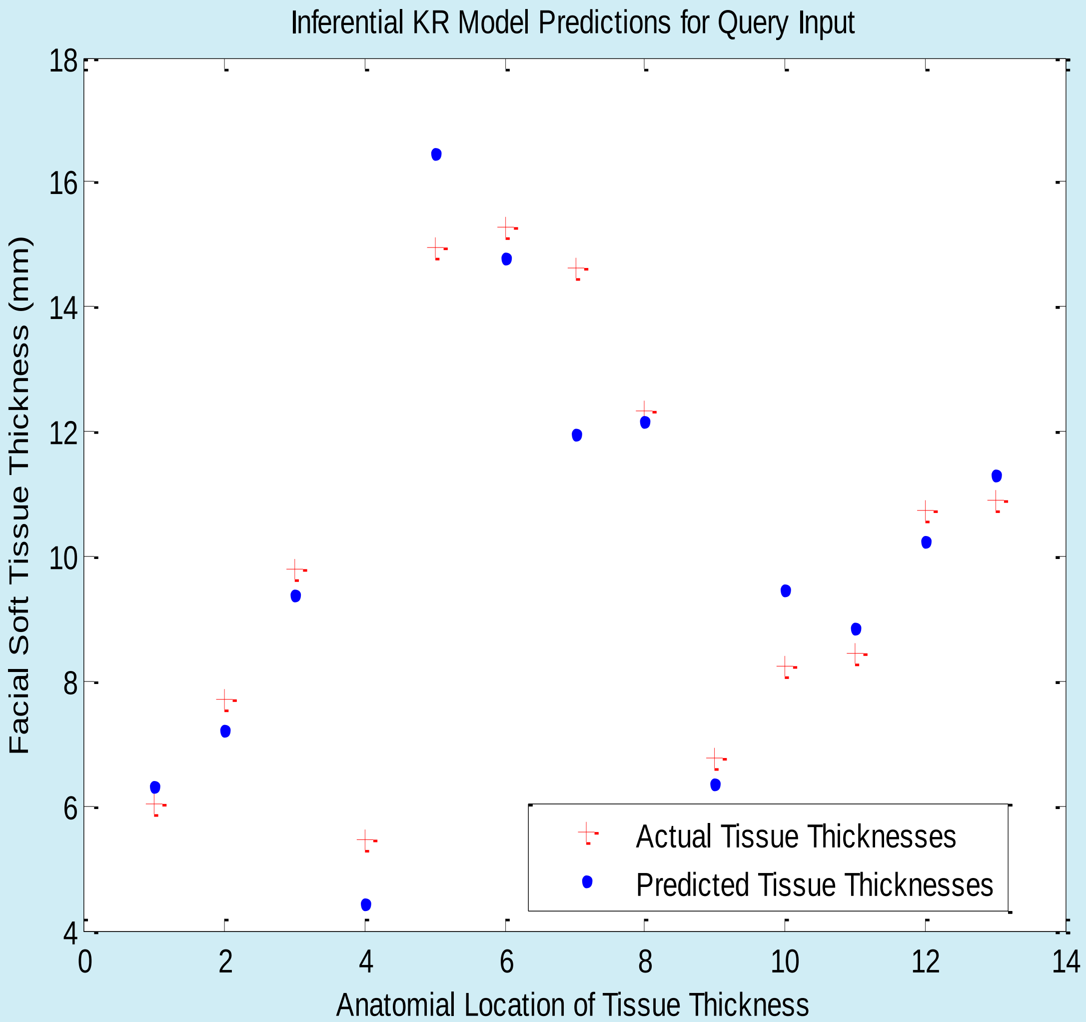
Prediction Uncertainty	Model RMSE	Table RMSE	Similarity
19.66%	2.21 mm	3.07 mm	0.41

Average Performance Metrics for All HAKR Models Without Using Demographic Predictors

Technology Transition Workshop

NIJ National Institute of Justice

IKR Model Results



- Usually provides more accurate predictions
- CC variable selection used
- 13 separate KR models

Technology Transition Workshop

NIJ National Institute of Justice

IKR Model Results

Prediction Uncertainty	Model RMSE	Table RMSE	Similarity
20.5 %	1.89 mm	3.07 mm	0.81

Average Performance Metrics for All HAKR Models Using Demographic Predictors

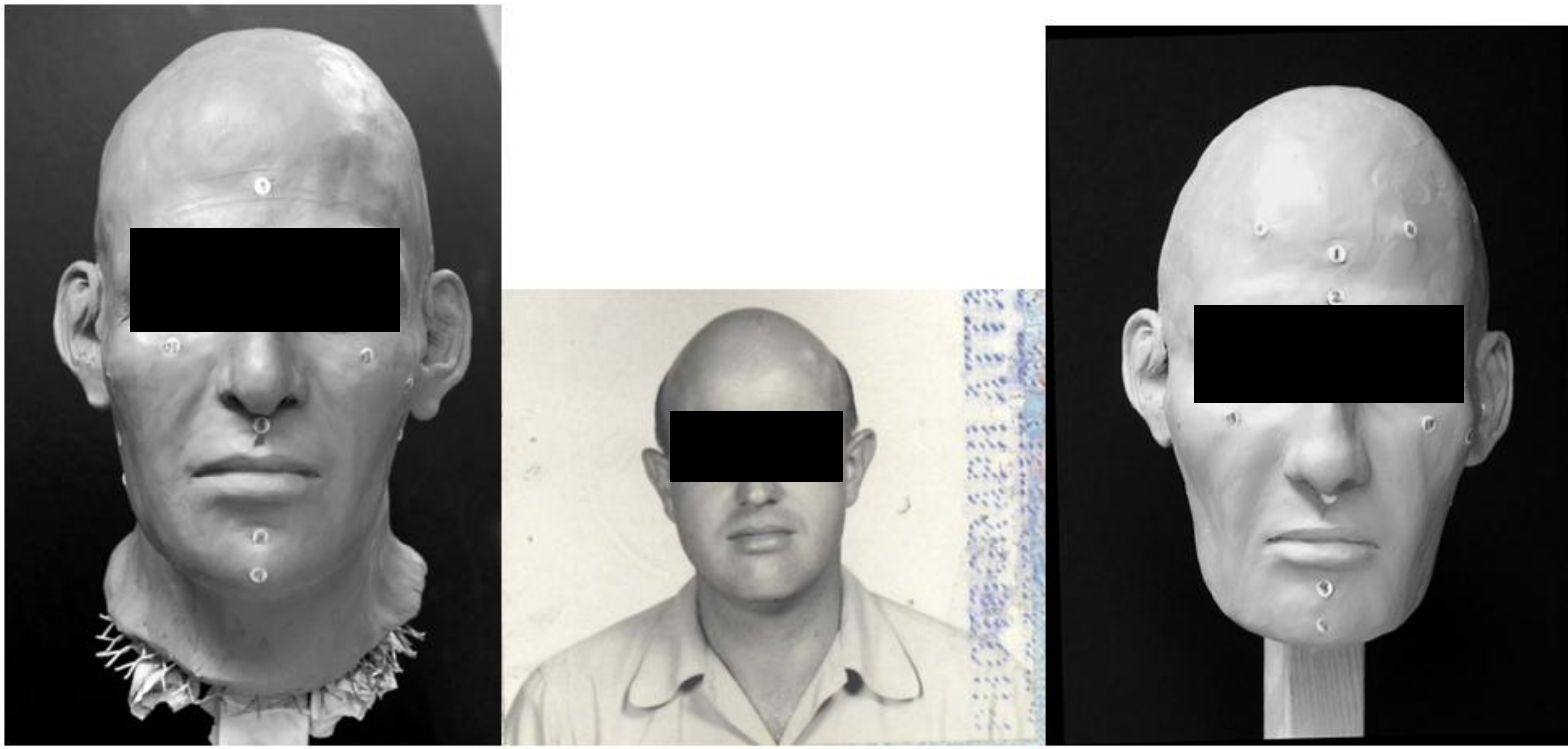
Prediction Uncertainty	Model RMSE	Table RMSE	Similarity
20.5 %	2.19 mm	3.07 mm	0.89

Average Performance Metrics for All HAKR Models Without Using Demographic Predictors

Technology
Transition Workshop

NIJ National Institute of Justice

Results



Old (Left) and New (Right) Reconstruction Methods Compared to Actual Living Photo (Middle) of Subject A

Technology Transition Workshop

Results

Old (Left) and New (Right) Reconstructions Compared to the Actual Living Photo (Middle) of Subject B

Technology Transition Workshop

NIJ National Institute of Justice

Results

Old (Left) and New (Right) Reconstructions Compared to the Actual Living Photo (Middle) of Subject C

Technology
Transition Workshop

NIJ National Institute of Justice

Conclusions

- The methodology and procedures required to collect and analyze the cranial data were developed
- The HAKR model and inferential models built with the 100 observations both yielded results with less error than the currently used tabled tissue thicknesses

Technology
Transition Workshop

Conclusions (Continued)

- **The demographics, weight and BMI, are the highest correlated predictors of tissue thickness among the 22 predictors used in this pilot study**
- **Demographics, especially weight and BMI, are usually not provided to the forensic artist; but technologies could be used to help estimate them from skeletal remains (Moore, 2008)**

Technology
Transition Workshop

NIJ National Institute of Justice

Conclusions (Continued)

- **The three-dimensional clay reconstructions resulted in noticeable improvements when using the developed model compared to the currently used "normal" tissue thickness tables**

Technology Transition Workshop

NIJ National Institute of Justice

Cited Scientific References

- Moore, M.K. Body Mass Estimation from the Human Skeleton. Ph.D. Thesis, The University of Tennessee, Knoxville, TN, 2008.
- Stephan, C.N. Anthropological Facial "Reconstruction" – Recognizing the Fallacies, "Unembracing" the Errors, and Realizing Method Limits. *Science & Justice* 2003, 43(4): 193-200.
- Taylor, K.T. *Forensic Art and Illustration*; CRC Press: Boca Raton, FL, 2001.
- Vargas, J.E.; Sucar, L.E.; Salas, M. Predicting the Most Probable Facial Features Using Bayesian Networks, Mathematical Morphology and Computer Graphics. *In Computer-Graphic Facial Reconstruction*; Clement, J.G.; Marks, M.K. (Eds.). Elsevier: Oxford, 2005.

Technology
Transition Workshop

NIJ National Institute of Justice

Additional References

- Bass, W.M. *Human Osteology: A Laboratory and Field Manual*; Missouri Archaeological Society: Columbia, 1995.
- Hines, J.W. Empirical Methods for Process and Equipment Condition Monitoring. *52nd Annual Reliability and Maintainability Symposium (RAMS)*, Newport Beach, CA, 2006.
- Mahfouz, M.R.; Badawi, A.M.; Merkl, B.C.; Abdel Fatah, E.E.; Pritchard, E.; Kesler, K.; Moore, M.K.; Jantz, R.L.; Jantz, L.M. Patella Sex Determination by 3D Statistical Shape Models and Nonlinear Classifiers. *Forensic Science International* 2007, *173(2)*, 161-170.
- Rhine, J.S.; Moore, C.E.; Weston, J.T. , Eds. *Facial Reproduction: Tables of Facial Tissue Thicknesses of American Caucasoids in Forensic Anthropology.* Maxwell Museum Technical Series No. 1. University of New Mexico: Albuquerque, 1982.

Technology
Transition Workshop

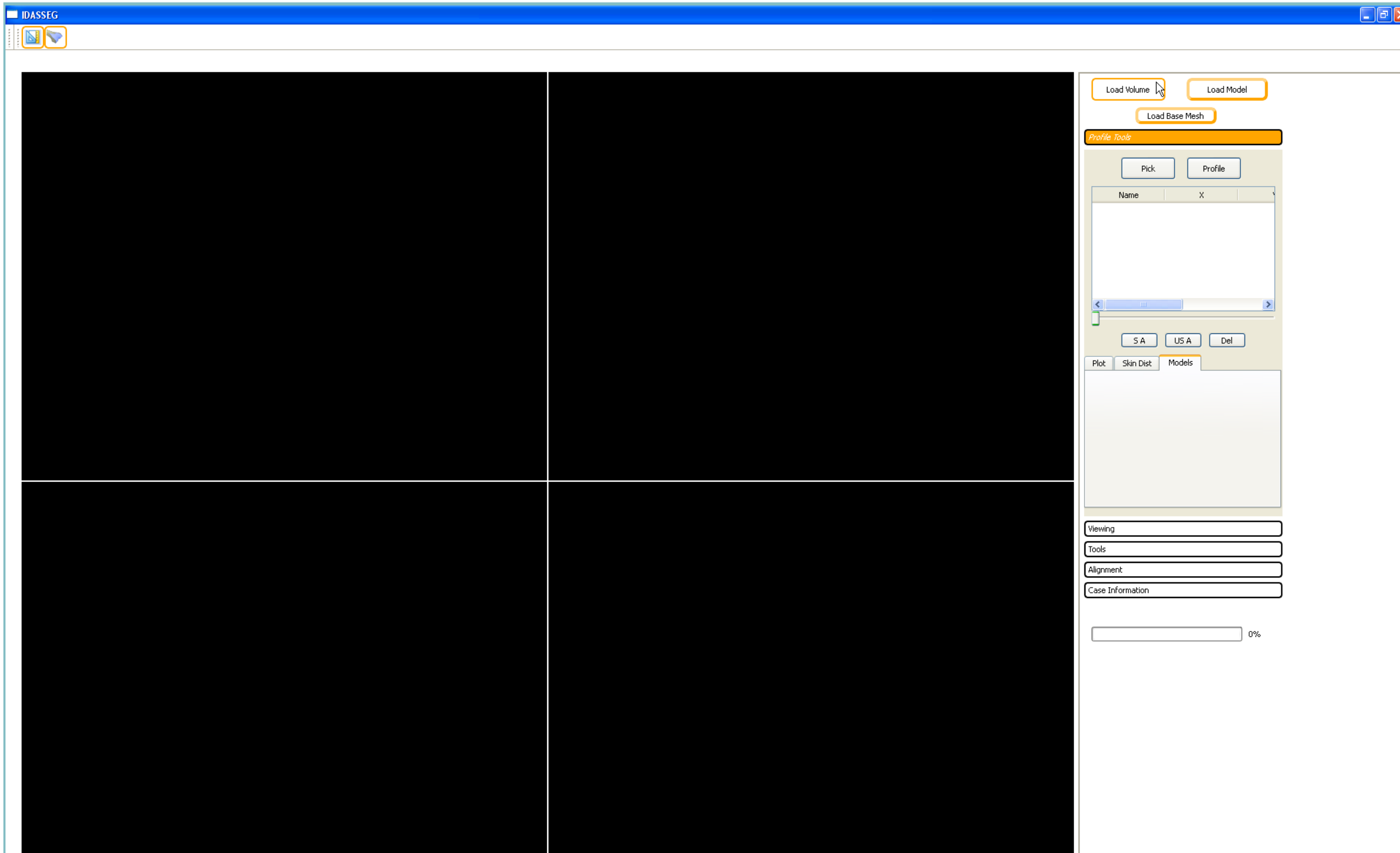
NIJ National Institute of Justice

Future

- **Apply the methods to a more complete data set**
  - **The original data set consisted of 100 males who were predominantly older and overweight**
- **Make use of Automatic Feature Extraction System that can be used to more exhaustively search for good predictors of skin thickness**
- **Optimize the kernel based model which may also involve generating separate models using demographic information**
- **Generation of automated surface rendering using skin thickness atlases**

Technology Transition Workshop

NIJ National Institute of Justice



Technology
Transition Workshop

NIJ National Institute of Justice

Questions?

Technology Transition Workshops are a project of NIJ's Forensic Technology Center of Excellence, operated by the National Forensic Science Technology Center (www.nfstc.org), funded through cooperative agreement #2010-DN-BX-K210.

Technology Transition Workshop

NIJ National Institute of Justice

Contact Information

Mohamed R. Mahfouz, Ph.D.

307 Perkins Hall

University of Tennessee

Knoxville, TN, 37996

865-974-7668

mmahfouz@utk.edu

Note: All images are courtesy of Dr. Mohamed R. Mahfouz and the Center for Musculoskeletal Research at The University of Tennessee, unless otherwise indicated.

Technology Transition Workshop

NIJ National Institute of Justice