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# Escaping the 1D Bottleneck: An Online Framework for Applying Population-Level 3D Anthropometry to Design

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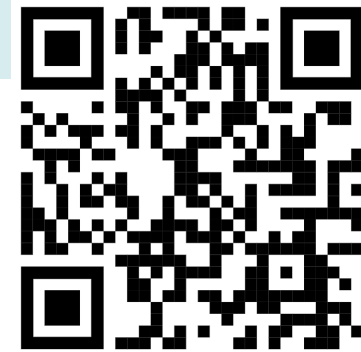
This research was supported by multiple organizations and collaborators, including:

- Amazon Inc.
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- U.S. Navy
- U.S. Air Force
- U.S. Marine Corps
- SENTIR Labs (STI-TEC)

Matthew Reed, PhD

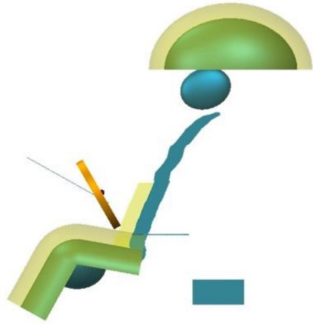
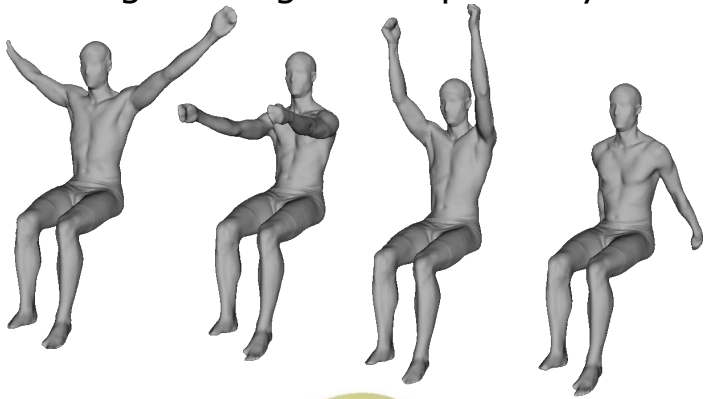
[mreed@umich.edu](mailto:mreed@umich.edu)

<http://mreed.umtri.umich.edu>



# Biosciences Group: Major Research Areas

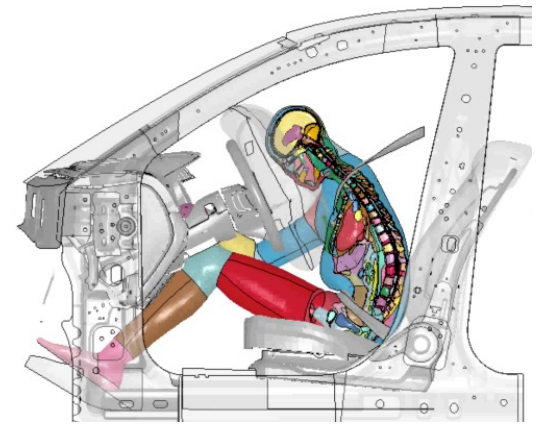
## Engineering Anthropometry



Vehicle Occupant Posture Prediction and Accommodation Modeling



## Occupant Crash Protection



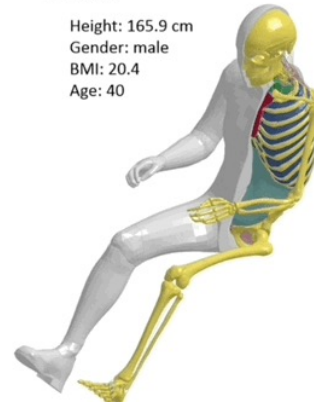
### Female

Height: 152.7 cm  
Gender: female  
BMI: 19.5  
Age: 40



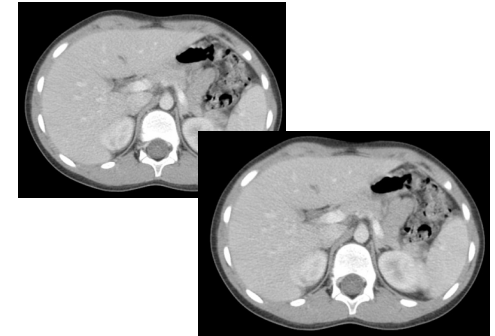
### Male

Height: 165.9 cm  
Gender: male  
BMI: 20.4  
Age: 40



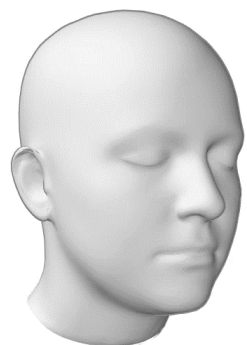
## Computational Human Body Modeling

Over 25 years of research with U.S. Department of Defense

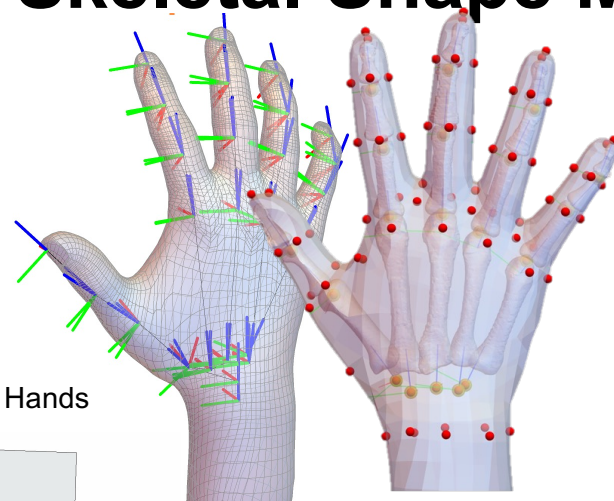
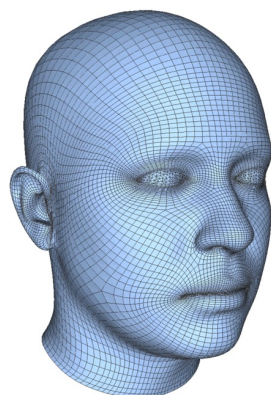


Injury Biomechanics

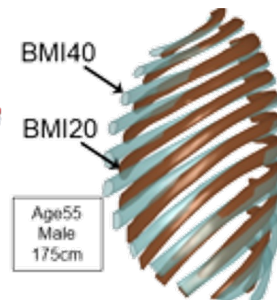
# Regional and Skeletal Shape Modeling



Head with accurate scalp



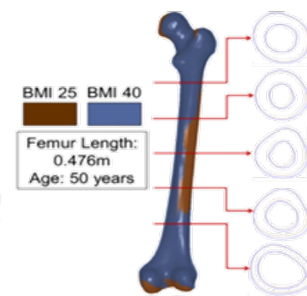
Hands



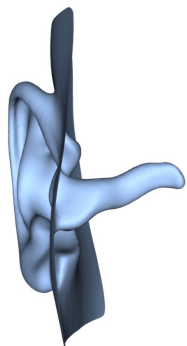
BMI40

BMI20

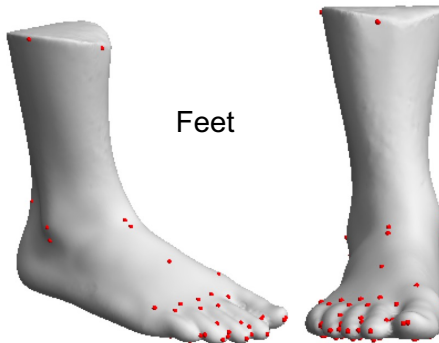
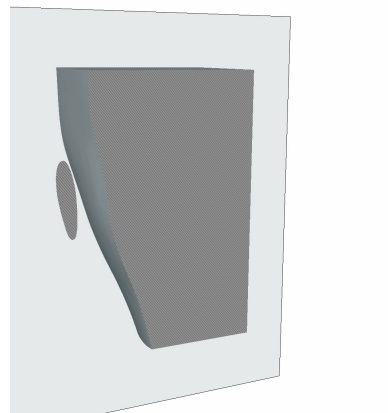
Age55  
Male  
175cm



BMI 25 BMI 40  
Femur Length:  
0.476m  
Age: 50 years

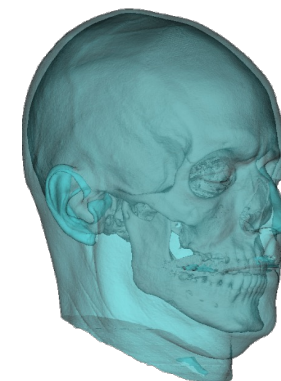
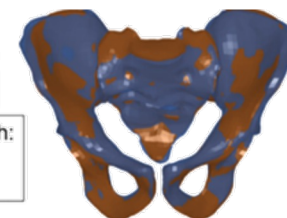


Detailed ear geometry with canal



Feet

BMI 25 BMI 40  
Bispinous Breadth:  
0.242 m  
Age: 50 years



skeletal structures

# Applied Anthropometry is Stuck in the 1950s

How do nearly all product designers find and use anthropometric data?

- do a Google search; when that fails, ask AI! or
- look in a reference text for a dimension that looks like it might be relevant
- select a 5<sup>th</sup> or 95<sup>th</sup> percentile value

or

- use a manikin, template, headform, or some other pre-defined reference: even when 3D forms are used, usually fewer than 6 and often **only one 3D form** is used

What are the problems with this approach?

- univariate
- one-dimensional data
- wrong dimension
- wrong population
- wrong size (manikin approach)

# Surely things are better for military applications?

Not much better:

- In the U.S., detailed **3D** anthropometric information for warfighters (e.g., ANSUR II) is generally not available to product designers; 10s of thousands of warfighters have been scanned, but only a few people have access due to privacy concerns
- Most designers are using univariate statistics from published reports
- Tools for actually using population-level 3D data in design are not available and hence aren't in acquisition requirements

What are the problems with this approach?

- often |
- ✓ • univariate
  - ✓ • one-dimensional data
  - wrong dimension (limited to what's been measured previously)
  - wrong population (surface Navy?)
  - wrong size (manikin approach)\*

# Thought Experiment: How would you do product design...

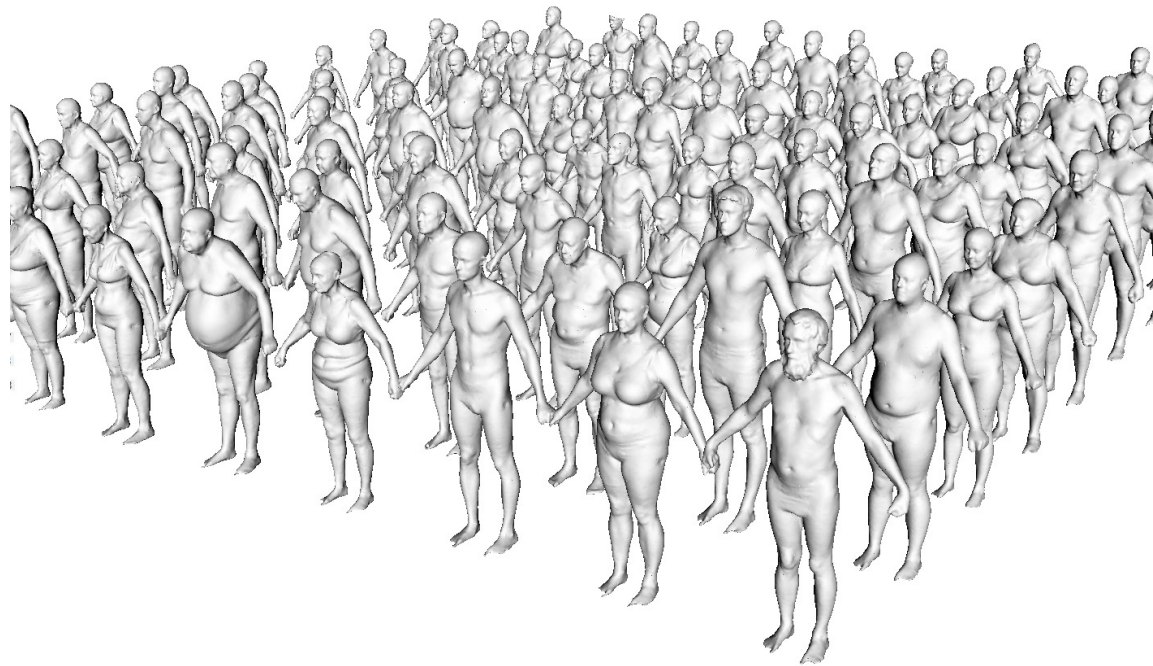
If you had infinite resources ....

and a time machine?



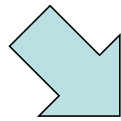
# Fantasy Design World

- Infinite physical prototypes!
- Try everything on everyone!
- Optimize designs (size/shape/adjustability/sizing etc.) across the whole population by doing physical try-ons!

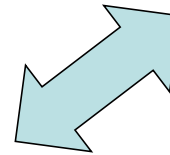


## Back in the Real World: Virtual Fit Testing

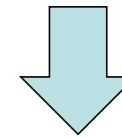
Individual-level population characteristics that affect product interaction



Model of product interaction



Concept of fit: how is the product supposed to fit and how do you know if it fits



Cost functions that convert product interaction outputs into a quantitative score

Simple idea: count the number of users in a population who obtain “good fit”

# VFT Data Requirements

## Population data:

- correct population
- correct variables
- can be more than anthropometry: strength, age, etc – anything we can know about the population that influences the interaction with the product

## Product interaction data:

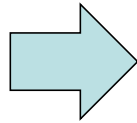
- objective and subjective outcomes from parametric, structured interaction (fit/accommodation) testing
- statistical relationships between outcomes and population variables

Need data for **individuals** who **represent\*** the **population**

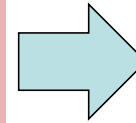
\* can be weighted or unweighted

# Simple VFT

individual-level 1D anthropometric dimensions



assumed 1:1 relationship between anthro and fit/accommodation



Multivariate binary cost functions (fits/doesn't fit)

Example: HFES Multivariate Accommodation Test Tool (MATT)

<https://my.hfes.org/online-store/publications>

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	<b>Multivariate Accommodation Testing Tool</b>														
2	IMPORTANT - Change only the green cells. The red cells will update automatically in response.														
4		Fraction Male		0.3 (between 0 and 1)											
5		Quantiles - Men			Quantiles - Women			Associated Dimension Value		Percent Accommodated					
6	Measures	5%	50%	95%	5%	50%	95%	Low	High	Men	Women	Both			
7	Stature (mm)	1634	1758	1882	1501	1621	1741								
8	BMI (kg/m^2)	21	28	39	20	28	43								
10	<b>Seated Measures</b>														
11	Abdominal Extension Depth (mm)	228	290	420	212	288	424								
12	Buttock-Knee Length (mm)	559	616	679	532	591	656								
13	Buttock-Popliteal Length (mm)	440	486	548	420	474	529								
14	Elbow Rest Height, Sitting (mm)	193	242	290	192	235	281								
15	Eye Height, Sitting (mm)	736	802	859	686	748	805								
16	Forearm-Forearm Breadth (mm)	482	566	681	410	491	633								
17	Hip Breadth, Sitting (mm)	333	382	455	353	421	530						99.4%	94.9%	96.2%
18	Knee Height (mm)	508	557	606	459	504	550						91.7%	99.7%	97.3%
19	Popliteal Height (mm)	390	434	478	338	382	426	340	470				90.1%	93.7%	92.6%
20	Shoulder Breadth (mm)	444	498	562	387	436	524								
21	Thigh Clearance (mm)	138	168	204	124	150	196								
22	Elbow Height Above Floor Estimated (mm)	615	679	739	554	618	681								
23	Thigh Clearance Above Floor Estimated (mm)	540	602	662	480	536	594								
24	Knee Depth Estimated (mm)	214	319	387	187	299	371								
25	Foot Depth Estimated (mm)	334	460	544	283	422	511								
27	<b>Standing Measures</b>														
28	Eye Height, Standing (mm)	1517	1640	1762	1400	1512	1631								
29	Elbow-Fingertip Length (mm)	431	470	512	386	421	462								
30	Elbow Rest Height, Standing (mm)	997	1084	1177	914	1001	1090								
31	Foot Length (mm)	244	266	291	220	239	260								
33								<b>Total Accommodation</b>			<b>86.8%</b>	<b>89.9%</b>	<b>89.0%</b>		

## But What About 3D?

To a reasonably approximation, <1% of 3D body shape data that have been gathered have ever been used in product design

### Typical Approaches to 3D Databases

**Faster tape measure:** extract the same 1D dimensions that would have measured by hand, proceed as if 1975 [VFT on 1D measures]

**PCA on the wrong variables:** pick some overall body dimensions (stature, sitting height, ...) do a PCA & generate boundary cases, find nearest neighbors in 3D, ignore the rest of the 3D data while using the boundary cases for specific analyses not related to these variables

# Why Haven't 3D Data Helped (much)?

Scan data is rarely and minimally used. Why?

- scan files are hard to use, effectively impossible for most designers; template fitting is essential but uncommon
- privacy limits access
- doing good scanning is hard (and still expensive)
- sampling bias is worse than with 1D dimensions
- statistical knowledge needed for shape analysis is not broadly distributed
- **few software tools available to do useful things with 3D data**
- **even fewer tools available to useful things at a population level**



Some good 3D work has been done for clothing, body armor, helmets, etc. by DOD researchers, but this has not resulted in widely used methods or software, even within the government

## Some of the Problems with 3D Scan Data

Typical standing scan  
before processing

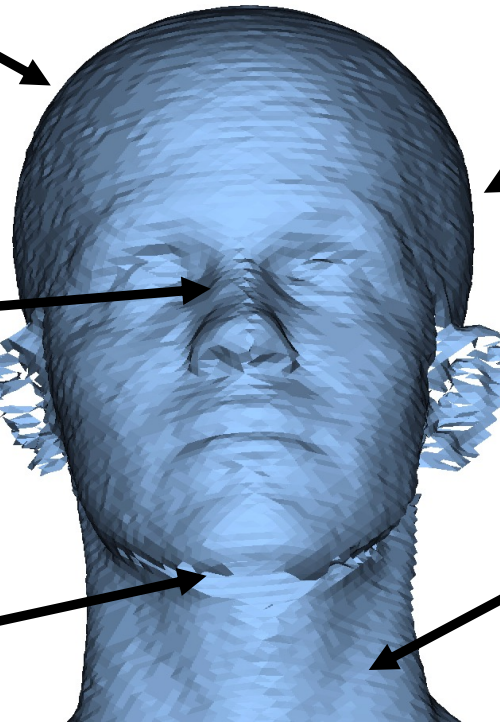
Hair artifacts

Not in useful  
coordinate system

Noise

Holes

Unstructured Mesh

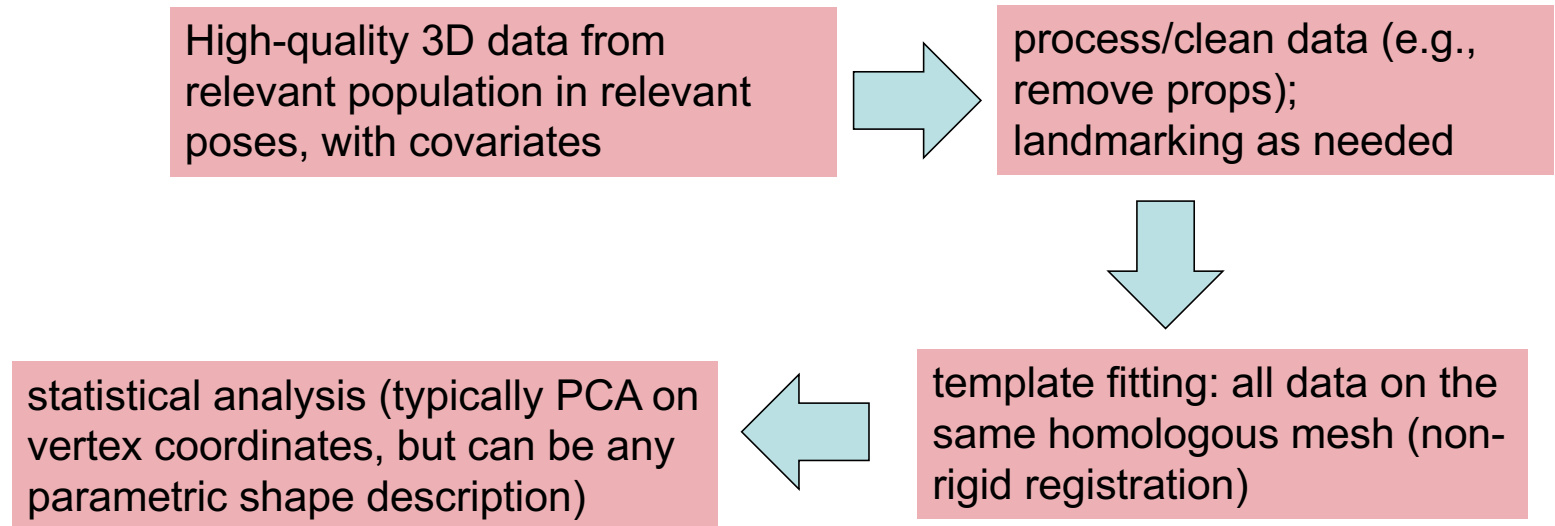


No widely available software well-suited for using 3D scan data

# What is Needed to Use 3D Data?

1. Software
2. Design methods
3. Education

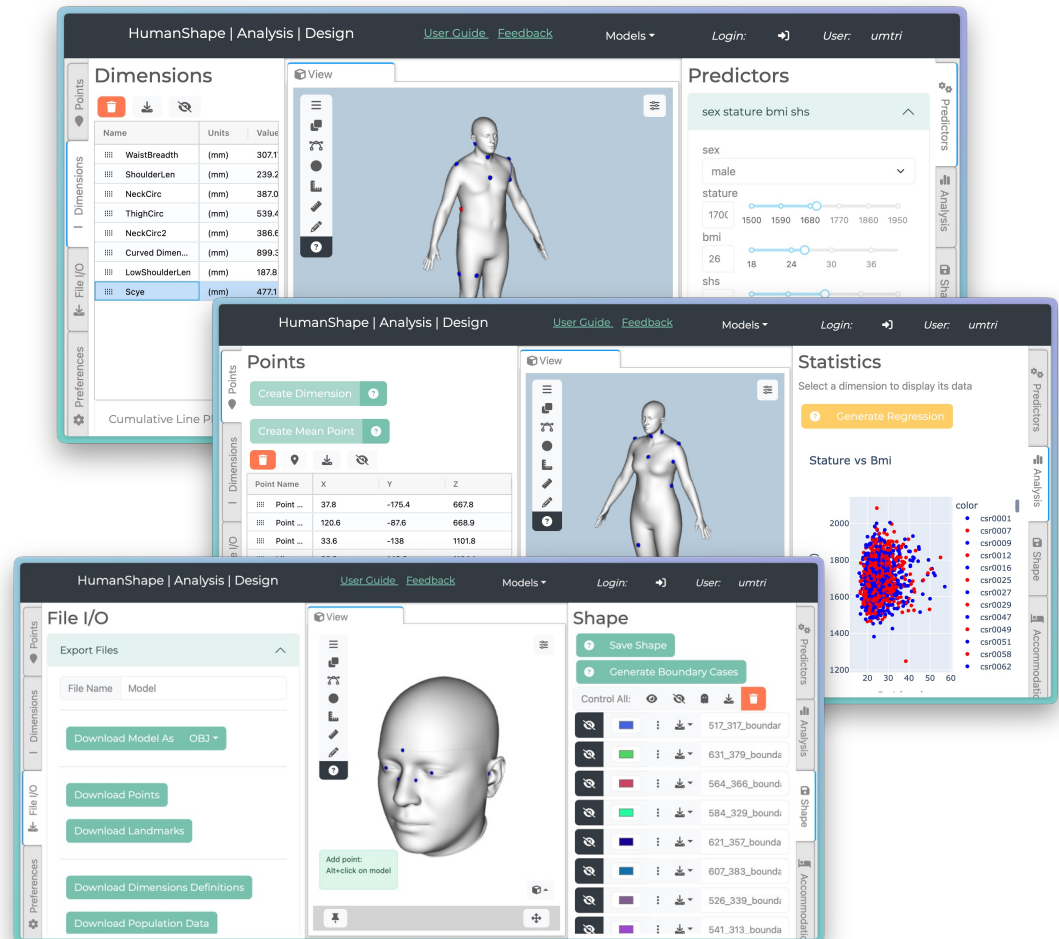
## Preliminaries: Database Development



# HumanShape App: Online Human-Centered Design

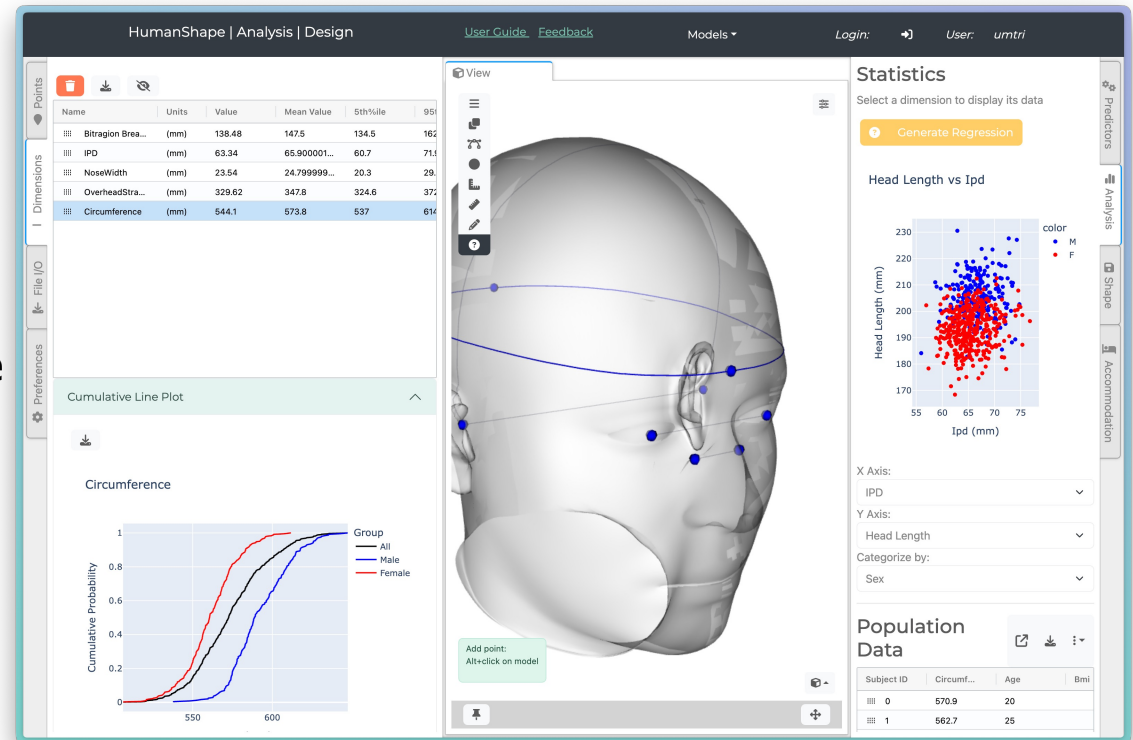
- Unified interface for working with all types of human body shape data, from whole-body to anatomical regions: hands, heads, ears, feet
- Online app means no software installation problems and accessible from anywhere
- Working with large populations of virtual avatars, not raw scan data
- Synthesis techniques ensure accuracy while eliminating privacy-related constraints

<https://HumanShape.app/>



# HumanShape App: Online Human-Centered Design

- User-defined measurements – not limited to predefined measures
- Point-to-point dimensions, single-axis measurements, curves, circumferences, angles, centroids...
- All dimensions are automatically computed for every individual in the population
- Statistical analyses of population distributions of user-defined measures for male & female



# HumanShape App: Functionality

User defined points

User defined dimensions: point to point, circumferences, surface curves, angles...

Pre-defined and user-defined regressions

The screenshot displays the HumanShape app interface. At the top, the title bar reads "HumanShape | Analysis | Design" with links for "User Guide" and "Feedback", and a "Models" dropdown menu. The user is logged in as "umtri".

The main interface is divided into several sections:

- Points Panel:** Contains buttons for "Create Dimension" and "Create Mean Point". Below is a table of points with columns for Point Name, X, Y, and Z.
- View Panel:** Shows a 3D model of a human head with several blue dots representing user-defined points on the face and head.
- Predictors Panel:** Lists variables for regression analysis: "sex", "head\_length", "head\_breadth", and "ttoh". Each variable has a dropdown menu or a slider. The "sex" dropdown is set to "male".

Arrows from the text boxes point to specific elements: one points to a point in the table, another points to a point on the 3D model, and a third points to the "sex" dropdown in the Predictors panel.

Point Name	X	Y	Z
Point ...	0.8	-78.3	16.4
Mirror...	0.8	77.9	16.6
Point ...	99.8	0.3	17.8
Point ...	-15.6	-87.8	21.5
Point ...	-6.5	-81.4	-36.3
Point ...	-1.9	-72.5	-9.6
Point ...	5.2	-77.5	8.9
Point ...	5.7	-76.3	2.2
Point ...	2.1	-76.6	-2.6
Point ...	-1.1	-75.2	-4.4
Point ...	-2.1	-72.7	-8.8
Point ...	-0.7	-79.5	-37.4
Point ...	-18.7	-88.2	20.6

# HumanShape App: Functionality

The screenshot displays the HumanShape app interface, which is divided into several functional panels:

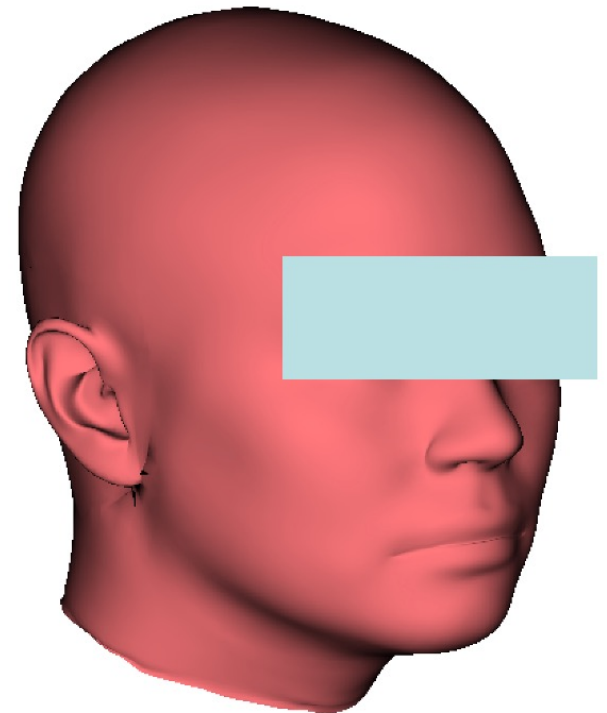
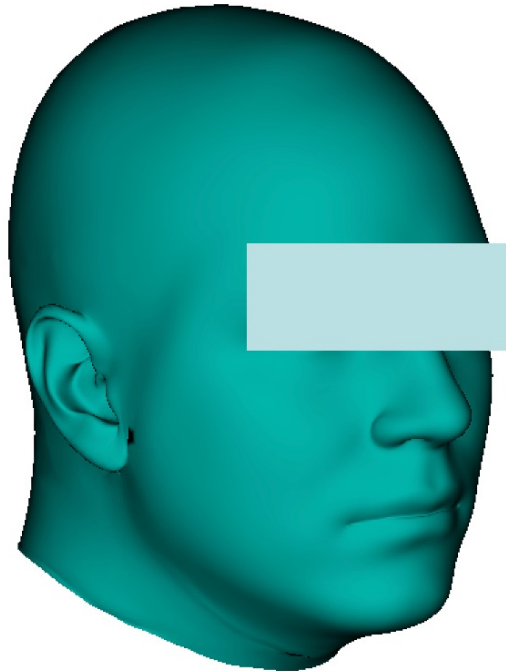
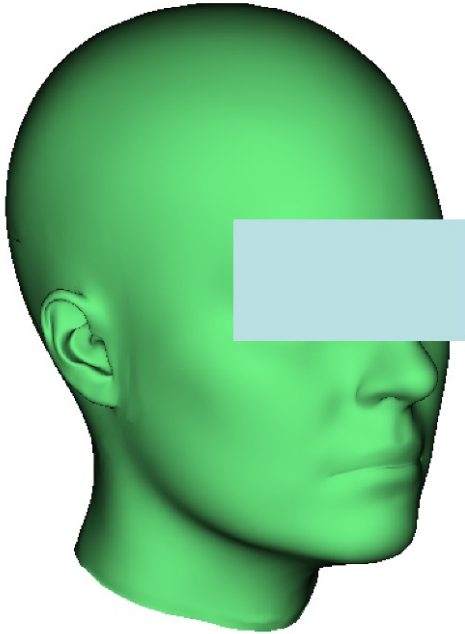
- File I/O Panel:** Contains options for downloading shapes, points, landmarks, dimensions, and population data, as well as an upload file section.
- View Panel:** Shows a 3D model of a human head with anatomical landmarks and dimensions overlaid.
- Statistics Panel:** Features a bivariate plot titled "nose base width vs Eartnose" with a "Generate Regression" button. It includes filters, axis labels, and a legend for "Boundary Cases".

Callouts with arrows point to the following features:

- Download shapes** (points to the "Download Model As" button)
- Download points, landmarks, dimensions, ...** (points to the "Download Points" and "Download Landmarks" buttons)
- Upload geometry** (points to the "Upload Files" section)
- Apply range filters** (points to the "Filters" dropdown in the Statistics panel)
- Bivariate plots** (points to the scatter plot in the Statistics panel)
- Boundary case generation on user-defined variables** (points to the "Boundary Cases" legend in the Statistics panel)

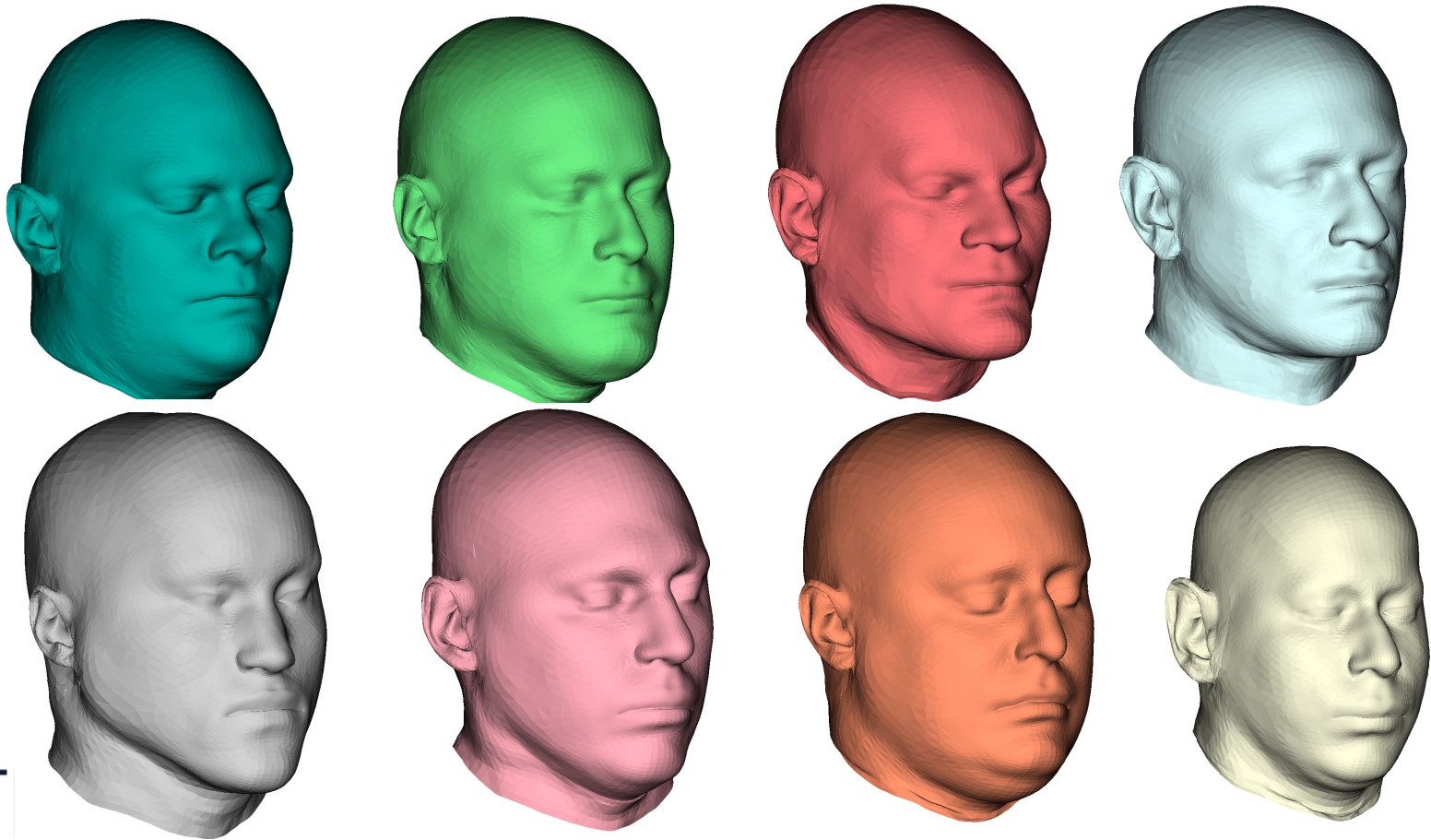
## Sidebar: De-Identification

Problem: privacy issues greatly restrict the use of head/face scan data



# De-Identification through Synthesis

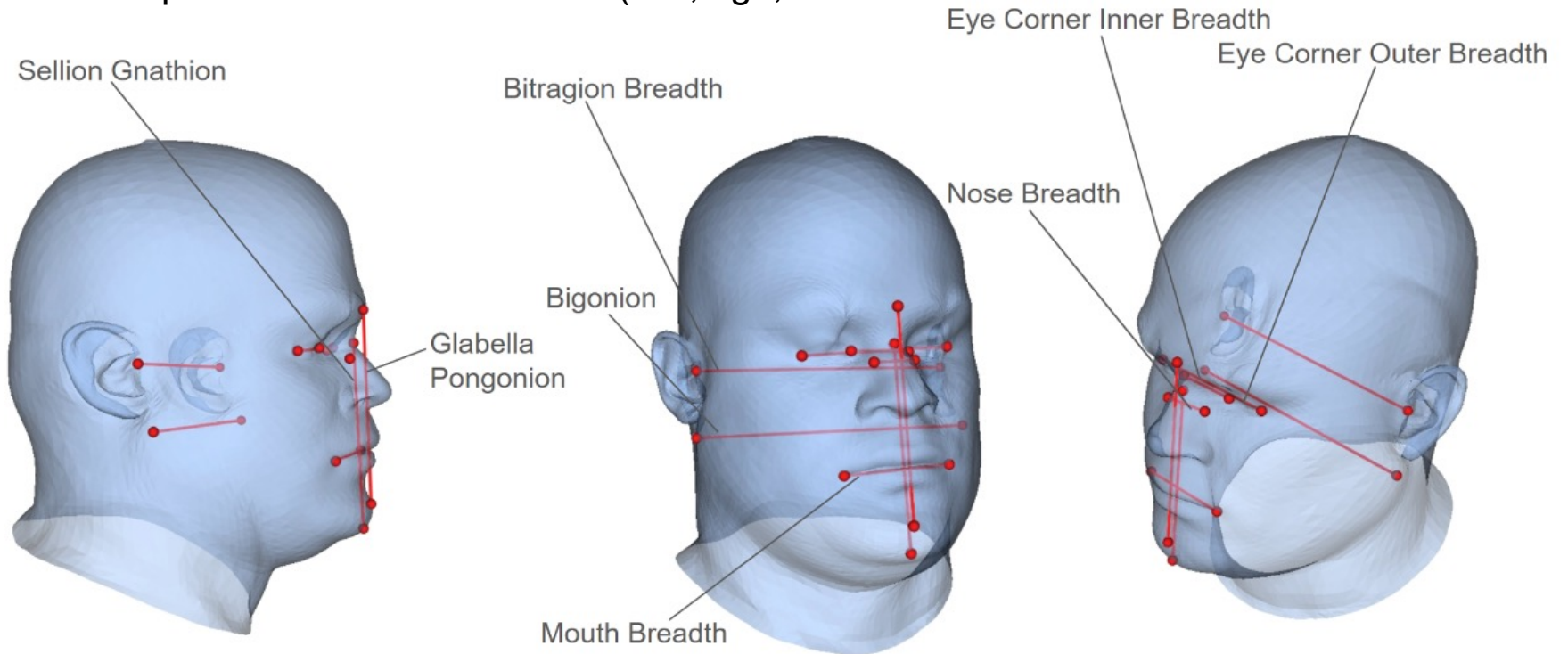
Synthesized versions of the same subject (none of these is an actual person)



# Head Synthesis Validation

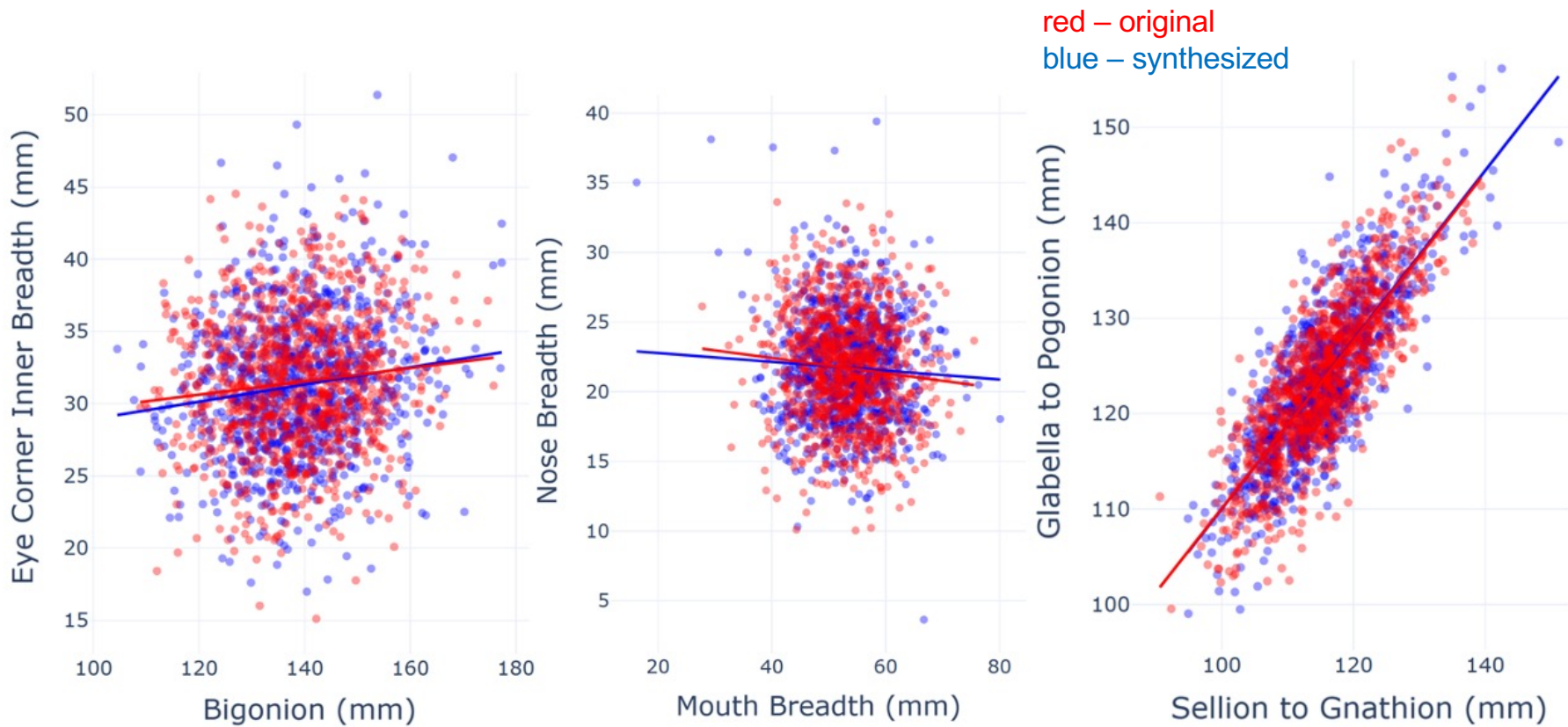
But does it work? The method must retain:

1. Summary statistics on head dimensions for population
2. Relationships among dimensions
3. Relationships with external covariates (sex, age, etc.



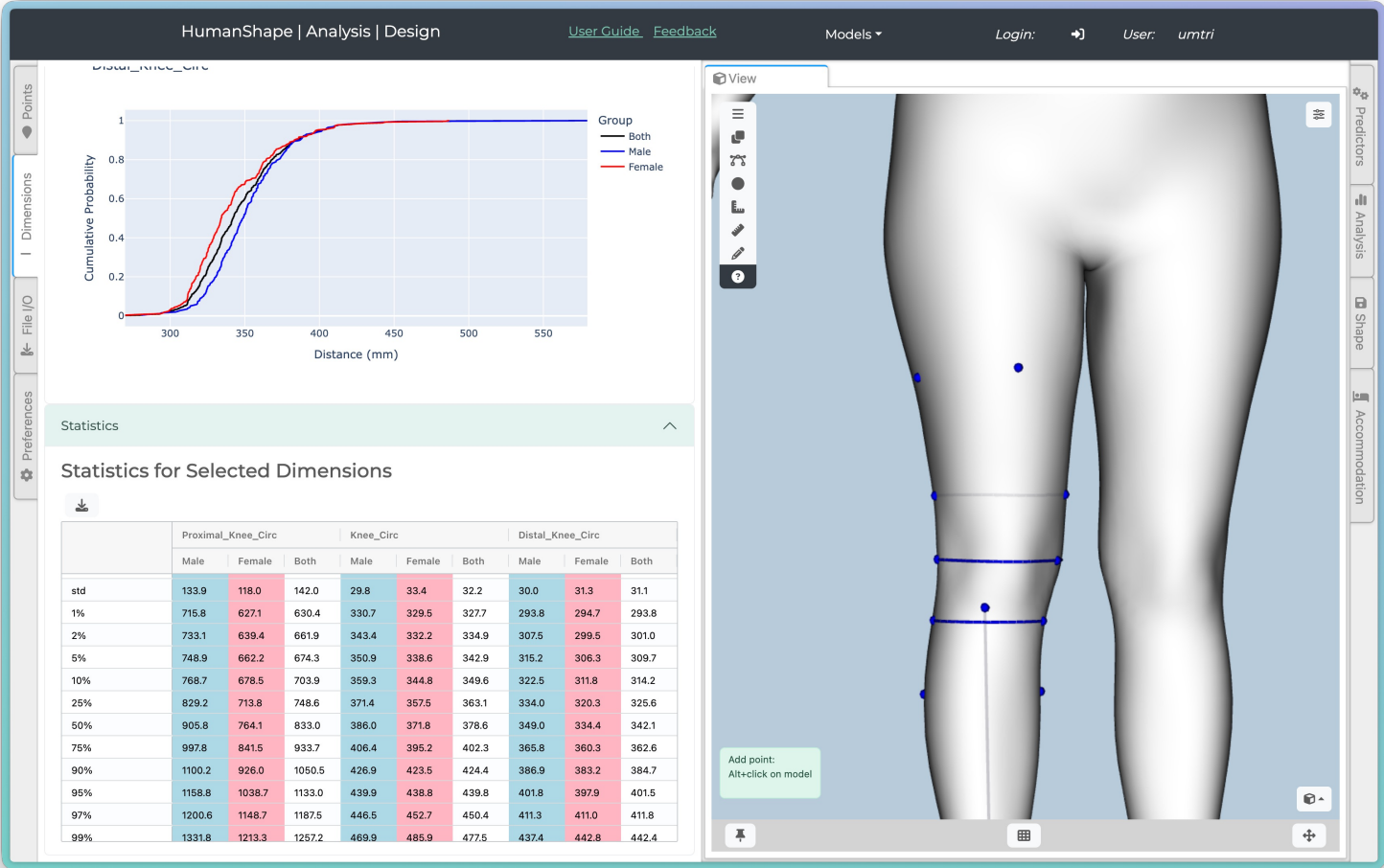
# Head Synthesis Validation

Statistical analyses for de-identified population are essentially identical



# Case Study: Knee Brace

Extract novel measures across the population



# Case Study: In-Ear Audio

Multivariate accommodation

The screenshot displays the HumanShape software interface. On the left, a 3D model of a human ear is shown with several blue dots and lines indicating measurement points and dimensions. The software's top navigation bar includes 'HumanShape | Analysis | Design', 'User Guide', 'Feedback', 'Models', 'Login', and 'User: umtri'. A sidebar on the left contains 'Points', 'Dimensions', 'File I/O', and 'Preferences'. A 'View' panel is open, showing the ear model. A 'Dimension' list on the right includes 'Total Result', 'outer canal...', 'Canal\_Heig...', and 'width'. A large 'Accommodation' window is overlaid on the right, featuring a search bar with 'outer canal height', 'canal\_height', and 'width' selected. Below the search bar is a table with the following data:

Dimension	Lower (mm)	Upper (mm)	M %	F %	Total %
Total Result			45	51.5	48.3
outer canal...	13	18	91.2	91.8	91.5
Canal_Heig...	8	12	58.8	66.7	62.8
width	7	10	78.8	83.6	81.3

# Case Study: Smart Glasses

Explore correlations and create boundary cases using regression or PCA

The screenshot displays the HumanShape software interface, which is used for analyzing and designing smart glasses. The interface is divided into several sections:

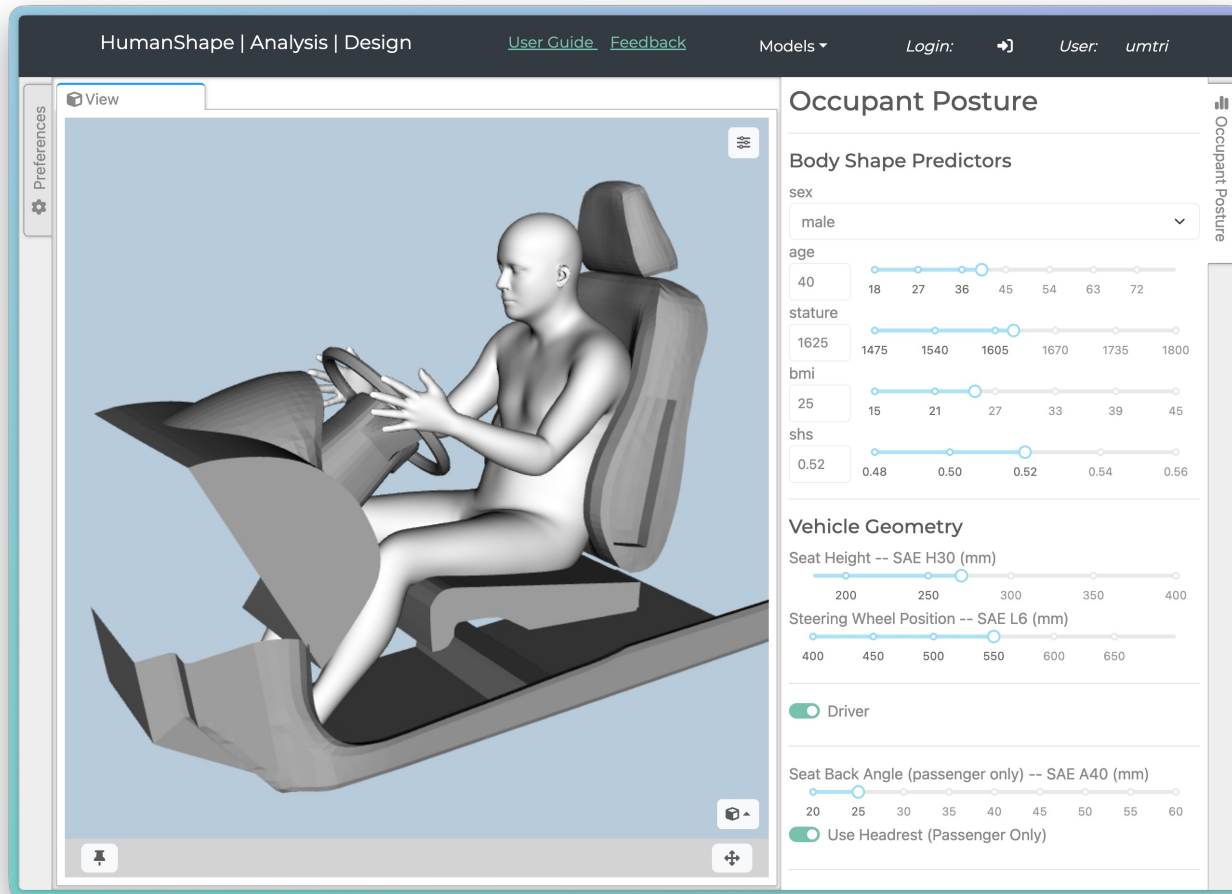
- Dimensions:** A table listing various dimensions of the head and glasses. The 'nose base width' dimension is highlighted in blue.
- Statistics:** A section titled 'Statistics for Selected Dimensions' showing statistical data for the 'nose base width' dimension, including mean, standard deviation, and percentiles for Male, Female, and Both groups.
- View:** A 3D model of a head wearing red smart glasses, positioned on a coordinate system. A 'Geometry Controls' panel is visible above the model.
- Shape:** A panel on the right side of the interface for controlling the shape of the glasses. It includes buttons for 'Save Shape' and 'Generate Boundary Cases', and a list of boundary cases with their respective colors and names.

Name	Units	Value	Mean Va
Dimension 0	(mm)	130.2	128.5
nose base width	(mm)	24.7	24.5
breadth	(mm)	156.2	152.7
EarToNose	(mm)	98.9	97.2
MultilineSurface	(mm)	36.5	36.0
Dimension 2	(mm)	61.4	59.2
pinnaheight2	(mm)	61.4	59.2

	nose base width		
	Male	Female	Both
mean	24.8	24.3	24.5
std	2.9	2.5	2.7
1%	17.8	18.7	18.1
2%	18.9	19.2	19.1
5%	20.2	20.0	20.0

# Case Study: Vehicle Interior Analysis

Generate body shapes in realistic postures as a function of vehicle layout



# Case Study: Scan-to-Measurement

Upload a head scan, fit it, instantly get landmarks and all predefined measures, measure anything else of interest, and place it within a population

The screenshot displays the HumanShape Design App interface. The central view shows a 3D model of a human head with a brown mask overlaid. The interface is divided into several panels:

- Dimensions Panel:** A table showing measured dimensions.
- Statistics Panel:** A table showing population statistics for selected dimensions.
- Shape Panel:** Controls for saving, generating boundary cases, and fitting the model.
- Boundary Case Dimensions Panel:** A table for defining boundary cases.

Name	Units	Value	Mean
Dimension 0	(mm)	148.08	147.6
Dimension 1	(mm)	156.71	151.1

	Dimension 1		
	Male	Female	All
mean	155.6	148	151.1
std	6.1	5.8	7
1%	141.8	136.8	136.9
2%	144.9	137.5	138
5%	146.6	138.4	139.6

Bonus: get recommended mask size!

# Future Functionality: Parametric Product Models

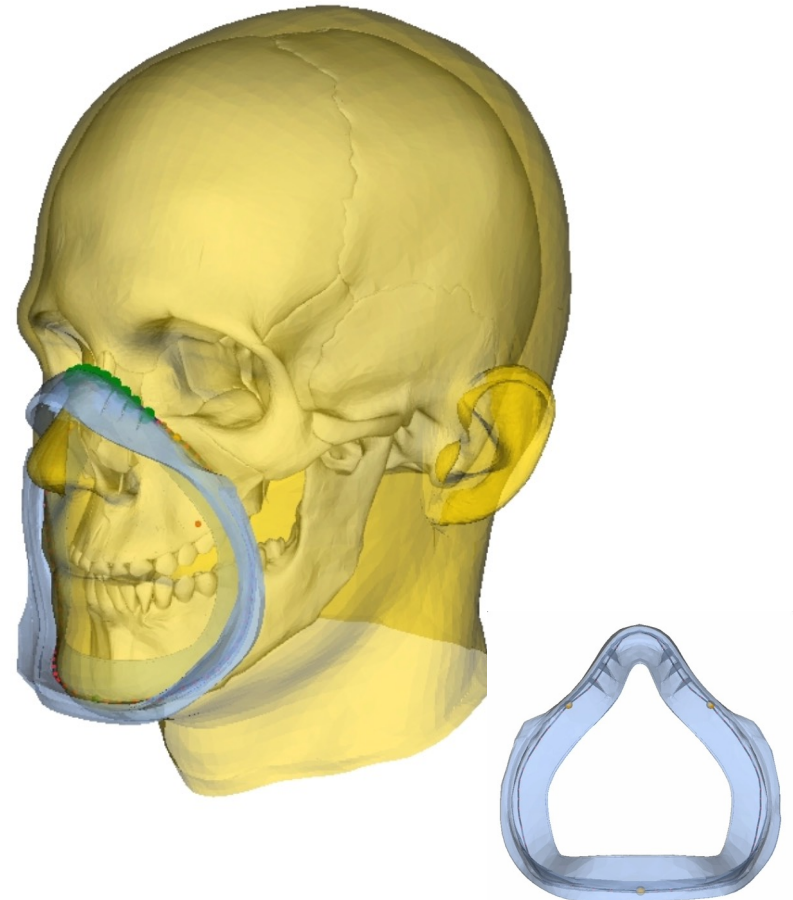
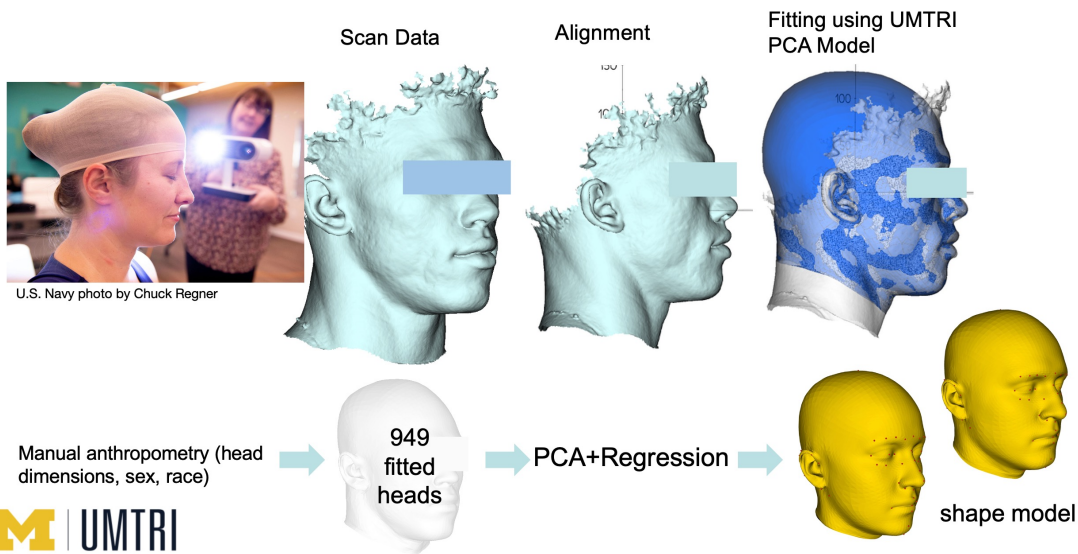
## Design wizards for common analyses

**Why:** Designers should not have to decide which aspects of body size & shape matter for their design, and figure out how to convert between body dimensions and product dimensions

**What:** Generic, parametric design models for common analyses; input your parameters → get your targets for product **design variables** rather than **anthropometric variables**

# Case Study: Pilot Oxygen Masks (work in progress)

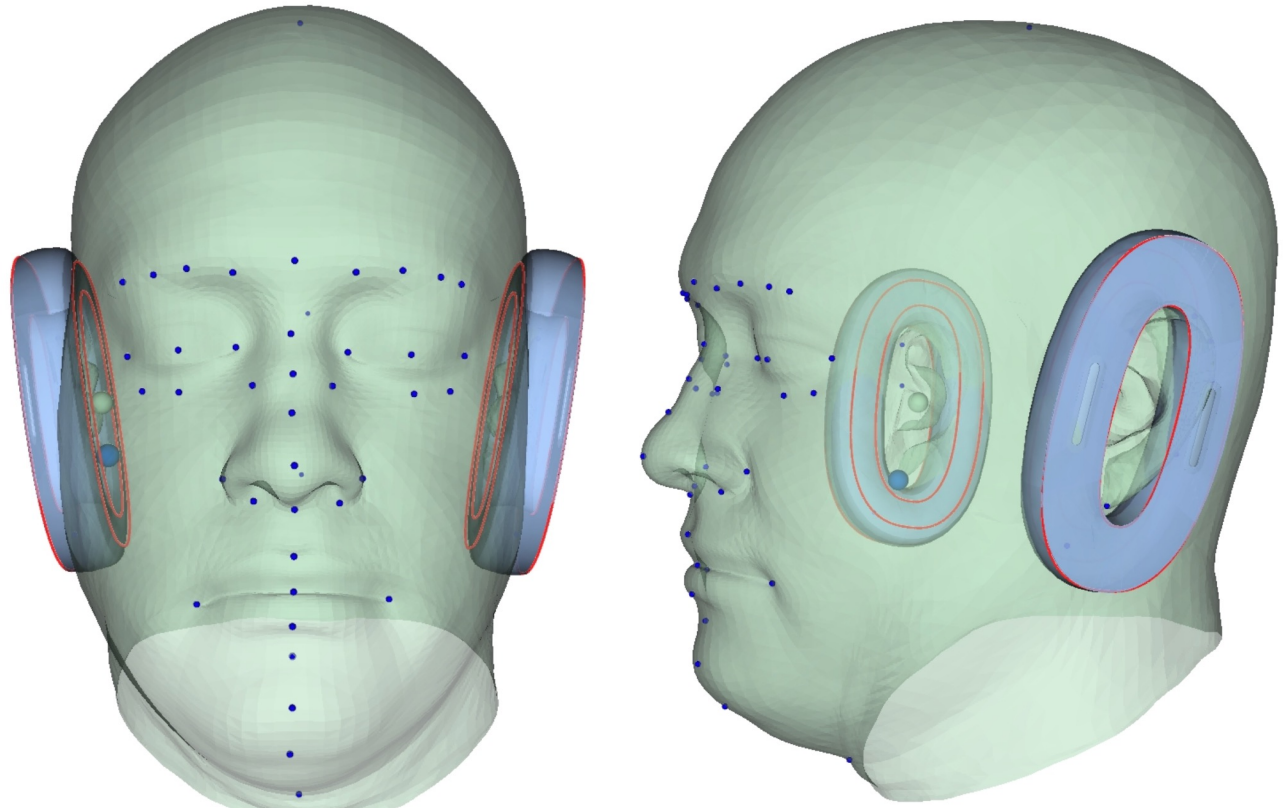
**Navy Dataset** Data from Lori Basham @ NAVAIR DREAMS lab under CRADA



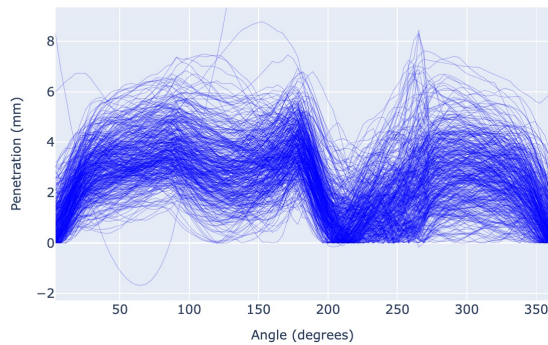
Collaboration with Gentex funded by Navy

## Case Study: Earcups (work in progress)

- Define parametric product model
- Conduct VFT across population
- Optimize design using quantitative metrics



Penetration Profiles



Collaboration with Gentex



## What about \*my\* population?

- We can fit any existing scan data, synthesize a matching, de-identified dataset, and add it to the app (U.S. Navy aircrew heads – thanks Lori!)
- Because we have statistical shape models, we can readily synthesize new populations that lie within shape spaces for which we have data.
- With data from thousands of U.S. and European military and civilian adults 18 to 80 years, and U.S. children ages 3 to 17 years, we can synthesize most “Western” populations of interest, including all U.S. military populations for which we have demographic descriptors (sex, age, race/ethnicity, stature & BMI if available)

## Limitations and Future Work

**Still an anthropometry tool:** needs to be enable the user to work in design variables, with the software creating the link to anthropometry

**Posing:** our BioHuman avatar is fully posable, but creating a good UI for posing is challenging; posing is necessary, but often creates more problems than it solves (valid posture prediction is much better)

**More anatomy:** we have linked skeletal geometry, organ geometry available

**Many more models:** foot, hand with grasp, head/neck with face/neck movement...

**Linkage to FE and musculoskeletal models:** We can immediately generate runnable models

**Product geometry interaction:** users can upload polygonal geometry, but the software doesn't play well with native CAD geometry; CAD system implementations?

**Customized populations:**

- currently no interface; requires us to generate the model (but this is programmatic)
- legal roadblocks due to addressable privacy concerns

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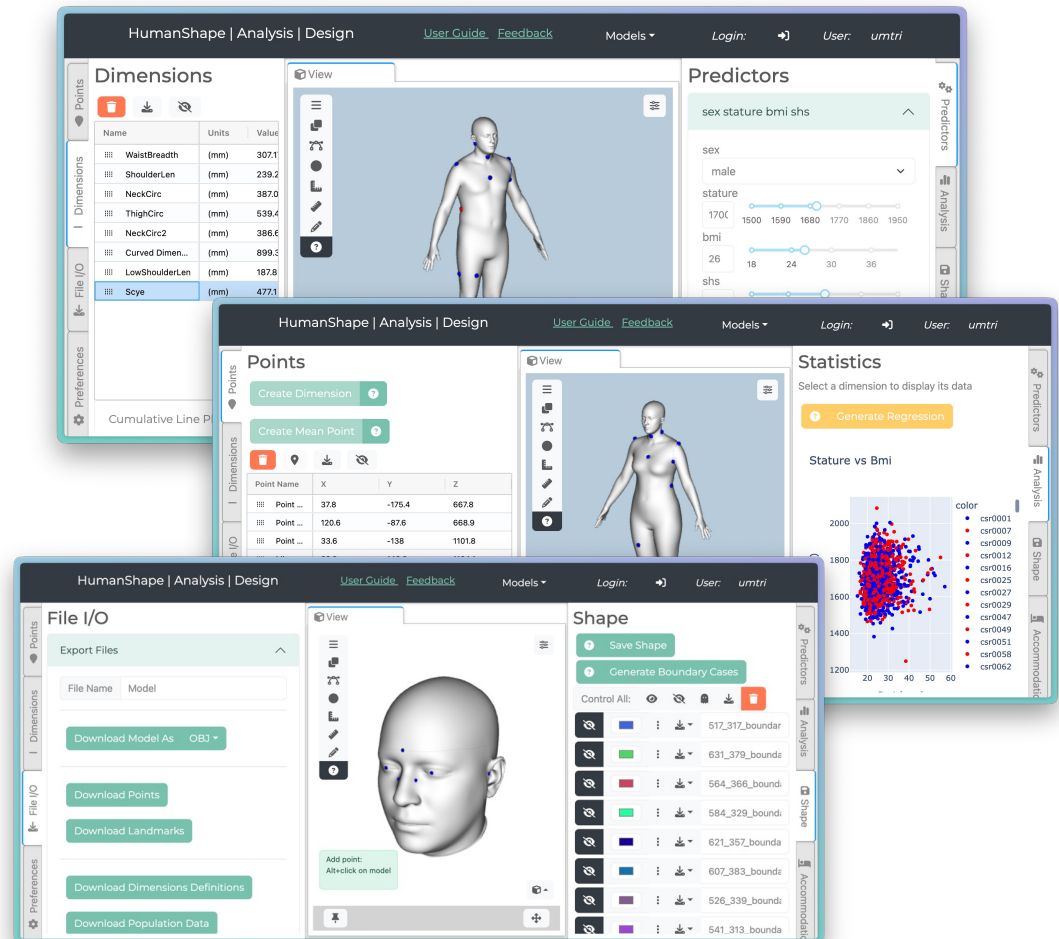
<http://mreed.umtri.umich.edu>



# HumanShape App: Online Human-Centered Design

- Unified interface for working with all types of human body shape data, from whole-body to anatomical regions: hands, heads, ears, feet
- Online app means no software installation problems and accessible from anywhere
- Working with large populations of virtual avatars, not raw scan data
- Synthesis techniques ensure accuracy while eliminating privacy-related constraints

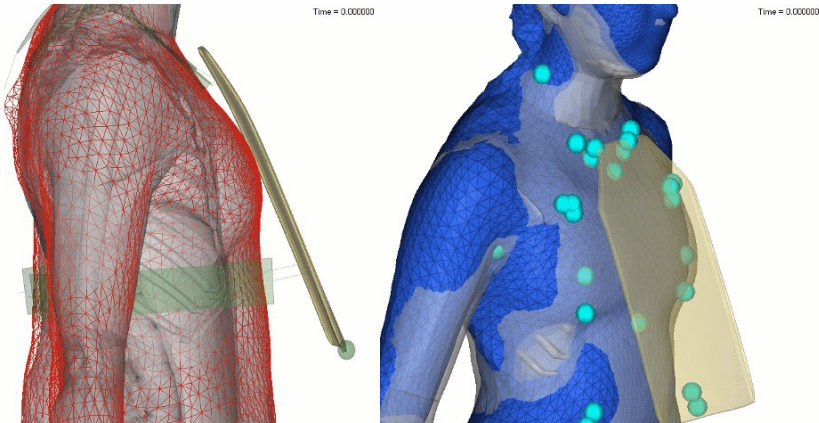
<https://HumanShape.app/>



# Additional Applications

Anything that fits close to the body:

- Glasses and goggles
- Head-worn displays
- Hearing protection
- Body armor
- Gloves
- Splints and other medical devices



Simulated plate interaction with parametric human model



Scans from UMTRI studies

