Beyond the Average :

Towards More Representative Human Body Models for Impact Simulations

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Master Project Meng 660`

Abstract:

Human Body Models (HBMs) are finite element representations of the human body used across the automotive industry to predict the occupant injuries in crash scenarios without the ethical and constraints of physical testing. The models that form the foundation of the most crash safety are built around a single baseline: the 50th percentile adult male. This representation leaves a major gap in injury prediction for women, child, older adults and people with body dimensions outside the assumed normal.

This project develops and document a structured workflow for modifying existing, validated GHBMC Human Body Models to represent diverse targets. Using the PIPER framework, 4 scaling and morphing methods were applied across 5 baseline models spanning child, adult male and adult female profiles. The methods include Child Age Based Scaling, Contour Repositioning, Kriging Deformation and Shaping scaling (BETA). The result demonstrate that all 5 models were successfully modified without rebuilding from scratch, and that the choice of method must be matched carefully to the modification targets. The modified models are ready to be exported to LS-DYNA, Abaqus and HyperMesh. This work makes a reproducible pipeline towards more representative crash simulations libraries.

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Introduction and Background

Motor vehicle crashes remain one of the leading caused of injury and death globally. In the United States alone, the National Highway Traffic Safety Administration (NHTSA) reports 10 of 1000s of traffic fatalities yearly, with millions more in serious injuries. The engineering response using human dummies towards high fidelity computational simulation using finite element (FE) Human Body Models (HBMs).

An HBM is a detailed validated representation of the human body built using finite element methods. These models are interconnected in millions of nodes and elements, each assigned material properties from biological tissue testing. When subjected to simulated crash conditions in solvers such as Ls-dyna or Abaqus, HBMs predict how forces through the body and identity which tissues are at risk if injury. Unlike crash test dummies, which is measured through acceleration and force at sensor locations, HBMs capture the internal biomechanical response across the entire body, including soft tissues, bones, internal organs and the nervous systems.

Automakers including General Motors, Honda, Hyundai, Ford and Nissans rely on HBMs in there vehicles safety development pipelines to evaluate restraint systems, interior geometry and airbag development strategies. Researchers use them to derive the injury curves and assess compliance. The computational nature of the HBM testing enables rapid iteration testing, varieties scenario and occupant population analysis that would be impossible with a Human dummy.

The Foundation of the HBM development has a adult male baseline of 50th percentile figure representing a roughly 5 foot 9 inches 171 pound male. This baseline races it roots in crash dummy development in the late 1970s. When the standard crash dummy used in NHTSA 5 star vehicle testing was developed in 1978, it was modeled after this same figure. The assumption embedded in that choice was that the male body, at median size serve as a sufficient proxy for all vehicle occupant.

Figure 1

M50-0

5’9’’ 161 lbs

That Assumption has been challenged repeatedly over the past 4 decades. The problem is not the simply that the average male dummy is the wrong size for the women or child. It is that the biomechanical validation response of the human body to crash loading varies substantially across different body types and the injury mechanism involved are not linearly scalable from on body to the another body type. The distribution of mass, the geometry of the pelvis, the stiffness of the thorax and spine all differ in ways that directly consequences for the injury predictions.

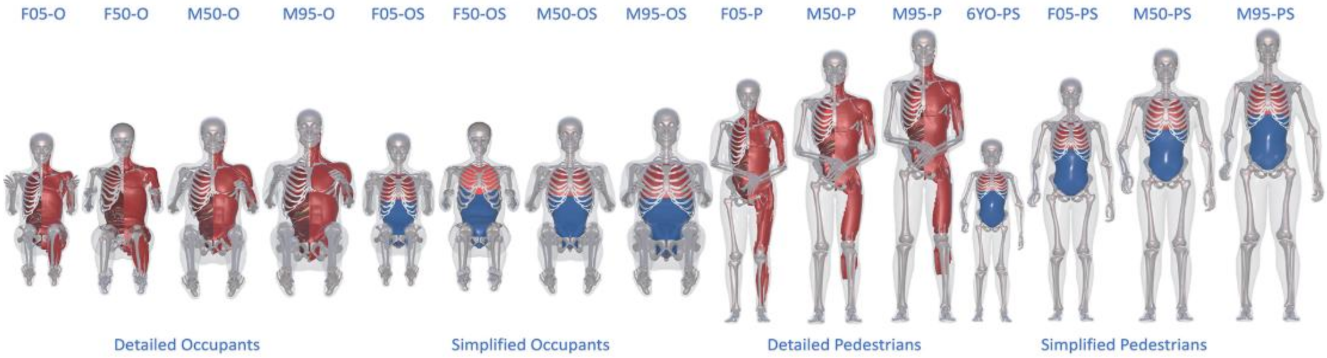
This gap has measurable consequences. Research through the insurance institute for highways safety and NHTSA has consistently shown that female occupants face higher injury in 26 percent of crash injury models studied, with most moderate severity injuries. Female rider are dramatically more likely to suffer lower injuries compared to mall riders and the risk for neck, chest and abdominal injuries are also elevated. Despite the evidence. As of 2025 Female dummies were not required under the standard crash testing protocols.

Children represent an equal critical gap. Pediatric HBMs are rare, and those that exit are based on a single age or size range. Yet a 3 year old, 6 year old and 12 year old are biomechanically bodies with very different injury susceptibilities. The Skeletal geometry, bone, head to body mass ratio and stiffness all change dramatically across childhood. Crash safety systems are designed based on a single child size cannot protect the full range of pediatric occupants.

Problem Statement

The crash safety community has recognized the representation gap for decades and yet no has done anything. Building a new fully validated Human Body Model is an Extraordinarily undertaking. The process requires reconstruction of internal anatomy, construction of the finite element mesh, material property assignment for Tissues and multi stage validation against data. The timeline for developing a single stage is measured in months to years. The cost to runs into millions of dollars. As a results, the industry has concentrated its investment in a small number of models, most of them centered on the adult male baseline.

The Global Human Body Models Consortuim (GHBMC) founded in April 2006 and supported by automakers including General Motors, Honda, Hyundai, Nissan with NHTSA as a sponsor representing one of the Most significant efforts to expand this library. The GHBMC has developed a family of models ranging from 5th percentile female to a 95th percentile male, including pedestrian and occupant variants and a 6 year old child model. This is a substantial contribution but it sill represents only a handful of human anthropometry. A 5th percentile female and a 25th percentile female are not the same body. A year and a 10 year child have meaningful of different biomechanical properties.



GHBMC.com

This gap is to develop methods that can modify existing validated models to represent new anthropometric targets, rather than building new models from the ground up. This approach preserves the validated biomechanical properties of the baseline model while adjusting it geometry to match a target individual. If it done carefully the deformed model retains the tissue level accuracy of the original and gains the geometric representativeness of the target.

This is not a new idea. Mesh morphing and scaling have been explored in the biomechanic field for more than two decades. interpolation, principal component analysis based statistical shape models, and landmark based scaling approaches have all been applied to HBM personalization. What has been lacking is a standardized, open source, solver agnostic software framework that brings these methods together into a reproducible workflow accessible to researchers and engineers who are not computational geometry specialists.

That is the gap PIPER project, funded by the European commission in November 2013. The results was the PIPER framework an open source, modular software platform for positioning and personalizing HBMs using a standardized set of numerical methods. PIPER does not replace the need for validated baseline models, but it dramatically reduces the effort required to generate new model variants from those baselines.

Research Objectives and Scope

The primary objective of this project is to develop, document and demonstrate a complete workflow for modifying existing validated GHBMC Human Body Models to represent the diverse anthropometric targets using the PIPER v1.0.1 framework. The goal is to produce models that are geometrically representative of their target populations and are export ready for use in established crash simulation solvers, without requiring the models to be rebuilt from scratch.

- Evaluate the four scaling and morphing methods available in PIPER v1.0.1 (Child Age Based Scaling, Contour Repositioning, Kriging Deformation, and Shaping) and characterize the appropriate use case for each.
- Apply these methods across five baseline GHBMC models: the 6 year old child (seated and standing), the M50-O adult male, and the F5-O and F5-PS adult female models.
- Generate modified models spanning a range of anthropometric targets including children aged 3 to 12 years, an adult male modified for higher body mass, and adult females representing 5th to 95th percentile size ranges.
- Document the software workflow, file structure requirements, and configuration steps in sufficient detail to enable replication by other researchers.
- Identify the limitations of each method and of the PIPER framework as a whole, and recommend directions for future development.

Scope

This project is focused on the geometric modification and positioning of the Human Body Models. It does not include full biomechanical validation of the modified models against experimental impact data. Validation is acknowledged as the critical next step but falls outside the scope of the current project due to resources and time constraints. The modified model are characterized by their geometric outputs and their successful export simulation ready. Material properties scaling, which is an experimental feature in PIPER was not applied to this study.

Review

The body of literature documenting different crash injury risk across demographic groups is substantial and spans several decades. Early work focus on the observation that female occupants sustained higher injury rates than male occupants in comparable crashes, a finding that persisted after controlling for differences in crash type, vehicle size, and restraint use.

Research published by the NHTSA and analyzed using data from the Fatality Analysis Reporting System (FARS) and the Crash Investigation Sampling System confirms that the gap is real and persistent. A female driver or front passenger who is wearing a seatbelt is approximately 17 percent more likely to be killed than a comparable male occupant. For moderate injuries, women face statistically significantly higher risk in roughly one in four injury categories studied. The female body has different pelvic geometry, different thoracic stiffness, and a different center of mass relative to seated position, all of which affect how restraint systems interact with the body in a crash.

For children, the situation is even more nuanced. The head to body mass ratio in young children is substantially higher than in adults, making children more susceptible to head and neck injuries in rear impact crashes. The pediatric skeleton affects how loads are transmitted through bone and cartilage. The absence of fully developed abdominal musculature affects how seatbelt loads are distributed. Research using scaled child HBMs has shown that injury prediction error can be significant when an improperly sized model is used, even if the loading conditions are otherwise accurate.

A 2019 study published in Traffic Injury Prevention used parametric finite element human models to assess injury risks for older, obese, and female occupants in frontal crashes. The study sampled 100 occupants spanning a wide range of age, sex, stature, and BMI. It found U shaped relationships between occupant stature and head injury risk, strong effects of age and sex on chest injury, and significant correlations between BMI and knee thigh hip injury risk. This type of population scale analysis is exactly what diverse HBM libraries enable, and it cannot be conducted with a single baseline simulation approach.

HBM Personalization Methods

Mesh morphing approaches for HBM personalization have been explored across a range of computational methods. Landmark based scaling, in which anatomical landmarks are identified on both the source and target geometry and the mesh is deformed to minimize landmark displacement error, was one of the earliest practical approaches. These methods are computationally efficient but can produce poor mesh quality in regions between landmarks if the landmark density is insufficient.

Radial basis function (RBF) interpolation and Kriging are closely related approaches that generalize the landmark based concept by constructing a smooth deformation field across the entire model from a set of specified control point displacements. As documented in research published in the Journal of Biomechanical Engineering, morphing using Kriging interpolation has been widely adopted for generating models of different shapes and sizes from a validated baseline because it produces smooth deformation fields without abrupt transitions. However, computational cost scales with the number of control points, and element quality can degrade when large deformations are applied without iterative correction.

The PIPER project, funded by the European Commission and involving ten partners across industry and academia, synthesized these approaches into a single, open source framework. As reported in PIPER project publications and the CORDIS database, the framework was designed with explicit goals of being HBM agnostic, solver agnostic, and extensible, enabling researchers to apply standardized methods across different baseline models without reimplementing the underlying numerical approaches.

GHBMC Model Family

The Global Human Body Models Consortium was established in 2006 with the objective of consolidating human body model development into a single, coordinated global effort. The Wake Forest School of Medicine Center for Injury Biomechanics serves as the integration center, responsible for subject recruitment, medical imaging, anatomical model development, and experimental validation. The consortium produces and maintains a family of finite element occupant and pedestrian models spanning a range of body sizes and sexes.

The GHBMC naming convention encodes sex (F or M), percentile (05, 50, 95), and model type (O for occupant, P for pedestrian, S for simplified) into each model identifier. The M50-O, for example, is the detailed 50th percentile male occupant model, while the F5-O is the detailed 5th-percentile female occupant. The child model, designated 6YO, represents a 6 year old child. Each model has been validated against cadaveric experimental data for specific loading conditions, typically including frontal, lateral, and rear impact scenarios.

As noted on the GHBMC website, current consortium members include General Motors, Honda, Hyundai, Nissan, and Ford. NHTSA is a sponsor. The breadth of industrial participation reflects the genuine need for high quality, well validated HBMs that can serve as shared infrastructure across the automotive safety community.

PIPER Framework

PIPER stands for Position and Personalize Advance Human Body Model for Injury Prediction. This project was initiated in November 2013 under the EU framework. This Framework was developed till 2017, producing the PIPER v1.0.1 release which is the version that was used in this project.

The software was released under the GPL open source license and is freely available for download. The framework was designed from the outset to be both human body model, meaning it can work with any models that is opensource and not just GHBMC Models, meaning these models can be exported can be used with LS-DYNA, Abaqus, Hypermesh and other standard FE solver. These design choices reflect the goal of creating a shareable infrastructure that the community can input into other pipelines/workflow.

It should be noted that the PIPER project has be formally concluded and the software will no longer be maintained. Some HBM data for older version is no longer available from the project repository, which increases the difficulty of working with certain configurations. This legacy status is the one key limitations of the current project and is addressed in limitations sections.

The PIPER architecture consists of modules that build a PIPER Model upon importing the model geometry. This is a live anatomical interpretation of the finite element body model that's created whenever an FE model is imported. The PIPER Model stores mesh information, plus its interpreted anatomy, which includes its skeletal elements, body segments, its segment center of rotation locations and its surface geometry. Other modules share this same anatomy to interpret FE data properly and interact in a consistent manner. Several scaling modules exist none of which are directly compatible with one another along with multiple positioning and exporting modules that interact through the same PIPER Model data.

These modules operate by calling methods of the other modules while referencing only the PIPER Model itself. A workflow can thus be formed through simple sequential chaining of modules, where no module must know anything about the others. The GUI allows a user to position/scale a model while visualizing it in interactive 3D. However, the Python interface offers scripting functions that allow users to fully automate model creation and variation generation, as many researchers must make copies of an HBM, each being incrementally varied as part of an experiment, all with their position and scale changed as well.

File Structure

Working with the Human Body Models in PIPER requires understanding the 5 File structure that defines each of the Models:

File Type	Description
Keyword File (.k)	Contains the finite element geometry. This includes the node coordinates, element connectivity arrays, material property definitions, contact surface definitions, and boundary conditions. This is the file that defines what the model looks like and how it behaves under load.
Dynamic Input File (.dyn)	Contains the simulation physics setup. This covers time-step control parameters, load curve definitions, output request specifications, and solver configuration parameters. This file tells the solver how to run a simulation with the model.
Piper Model Repository (.pmr)	The master project file. The file organizes and links all model components into a single loadable package. It stores the PIPER Model interpretation, including landmark definitions, joint locations, and metadata required for scaling and positioning operations.
Source File (Kriging File)	The source file is the baseline PIPER child model, the original unmodified HBM that comes with the software, which has its own geometry, bone dimensions, and material properties already defined.
Target File (Kriging File)	target file is what you're trying to scale, the anthropometric data of your model The scaling process reads the source and reshapes it until it matches the target dimensions.

To have successful model deformation, understanding the relationship between the. pmr file and the corresponding. k file is vital, as many of the errors that pop up in PIPER's workflow occur due to contradictions between those files especially when the landmarks defined in the. pmr file reference node IDs or anatomy that was later changed in the mesh file. Lesson learned: The PMR file should probably be viewed and at times even edited in a text editor if you encounter issues with landing landmarks on subjects.

The source file is the parent HBM child that originally includes the mesh, geometry and the material properties that the PIPER tool loads and scales to. The target file contains the physical data about a particular subject that you're adjusting the source model to fit, such as their height, weight, segment lengths, etc. Inaccuracies between those files that especially have to do with the landmarks cause the most common types of errors that come up during the PIPER scaling phase.

PIPER Workflow

The general workflow for scaling/ repositioning an Human Body Model in PIPER follows 4 stages regardless of the method is used:

1. Load the Human Body Model (.PMR) file. PIPER constructs the PIPER Model, creating the anatomical interpretation of that geometry.
2. Select the scaling or positioning method from the module panel. Different methods require different input data, ranging from a target age value to a set of control point displacement to target the surface contour file.
3. PIPER computes the node displacement/ deformation. It involves the interpolation system to determine how each mesh node should be moved to produce the deformation. For Age Based Scaling, it queries the GEBOD regression database to determine appropriate scale factors.
4. Finally Reviewing the deformed/displaced geometry in the 3D viewpoint and exporting it to the desired solver format. For example exporting to LS-DYNA, Abaqus and HyperMesh format.

Model Overview

The Models used in this Project spans 3 different demographic categories: Child, Adult Male and Adult Female. Each model represents a different point in the anthropometric space and serves as the baseline for one or more modifications workflows. The table below summarizes the baseline models used.

Model	Baseline Specs	Methods Applied
Child- O (6YO Occupant) Figure 1	6 years old, seated occupant position, 3 ft 8 in, 46 lbs	Child Based Scaling, Contour Repositioning
GHBMC Child- P (6YP Pedestrian) Figure 2	6 years old, seated occupant position, 3 ft 8 in, 46 lbs	Shape Scaling
M50-O (Adult Male Detailed) Figure 3	50th percentile male, 5 ft 9 in, 161 lbs	Contour Repositioning, Kriging
F5-O (Adult Female Detailed) Figure 4	5th percentile female, 4 ft 11 in, 109 lbs	Kriging Scaling
F5-PS (Adult Female Simplified Pedestrian) Figure 5	5th percentile female, 4 ft 11 in, 109 lbs	Kriging Scaling

Figure 1

Child 6YO

Figure 2

Child 6YP

Figure 3

M50-O

Figure 4

F5-O

Figure 5

F5-PS

Model Naming Convention

The naming system used is a structured code to identify each of the model variant. Understanding this code is important when working with the model library and when interpreting the simulation results in the literature. The code breaks down in the following:

- First character is the Sec designation. F indicates female, M indicates Male.
- Number is the Percentile. 05 is 5th Percentile, 50 is 50th Percentile, 95 is percentile. The child mode is 6YO meaning 6 years old.
- Letter after is the Model category. O is Occupant, P is pedestrian and PS is Simplified pedestrian.

So M50-O is the detailed 50th-percentile male in seated occupant position. F5-PS is the simplified 5th-percentile female in pedestrian (standing) configuration. This naming system also extends to the modified models generated in this project: M29-O, for example, denotes an adult male occupant modified to reflect the body composition of a 29th-percentile male.

Importance of the Child Model

The child model is particularly important significantly because it is the one of the very few validated pediatric GHBMC Human Body Model available in the field. Most Human Body libraries focus on adult models and the very few on the child models that exist are often available only to the consortium members under restrictive licensing. The availability of the GHBMC 6YO model under the consortium licensing represents an important resource for pediatric crash safety research,

However, a single 6 year old child model cannot represent the full range of occupants. Children ages from 3 to 12 years represent a window of extremely rapid growth during which skeletal proportions, mass distribution and tissue mechanical properties change dramatically. The child age based scaling in PIPER was specifically designed to address the gap to provide a validated method for generating child models at ages other than the 6 year old baseline.

Scaling Methodology

Method 1: Child Age- Based Scaling

Child Age Based Scaling is a technique created for the PIPER model. It uses the GEBOD (Generator of Body Data) regression database to retrieve anthropometric dimensions that depend on age from a population of children collected during multiple growth studies. The GEBOD database encodes a way to calculate the dimensions of bones, body segments, masses and overall height in relation to age throughout childhood and adolescence.

The user specifies the age target and PIPER queries the database to return a corresponding set of Anthropometric Dimensions. This set of dimensions represents a set of target locations for the nodes representing segments. PIPER constructs the global deformation field to make nodes go to these targets while maintaining proportionality between body segment dimensions as they occur naturally in an infant or a growing child.

What's special about Child Age Based Scaling is its ability to reproduce the non uniform nature of human growth in children. As children age, their bodies scale nonuniformly. Head length scales more slowly relative to the rest of the body in middle childhood. For specific stages in development, the legs grow relatively faster than the torso. GEBOD regression can reproduce this effect, so the biomechanical validity of child Age Based Scaling is far greater than applying one global scale factor.

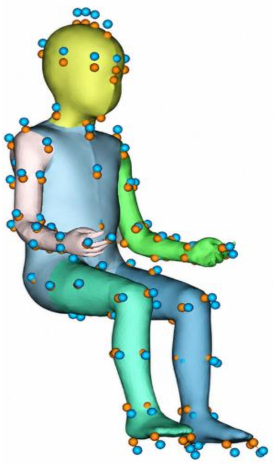


Fig. 1
Original
6-Year-old-3’ 8”

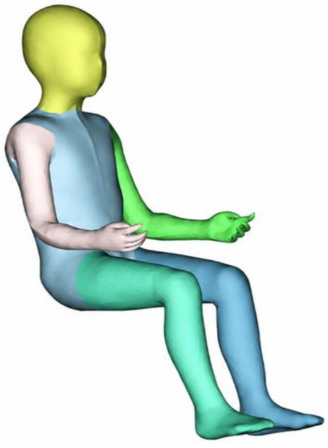


Fig. 2
Modified
8-Year-old-4’0”

In this Project, Child Age Based Scaling was used to generate child modes at ages of 3,8,9,10 ½ and 12 years from the baseline of 6 years old model. Th results show visually geometry changes with the expected increases in the limb length relative to the trunk and the overall stature that shows growth across the entire age range.

Method 2: Contour Repositioning

Contour Repositioning is a fundamentally different type of operation. Rather than scaling the entire model, it adjusts a specified anatomical region to match a target surface contour. The user defines the region of the body it choices and provides a target contour that specifies the desired outer surface shape of that region. PIPER then computes the displacement field required to deform the existing geometry onto the target contour.

The displacement computation is local: only the specified region deforms. Nodes outside the selected region are unaffected. This makes Contour Repositioning well suited for making localized shape adjustments, such as modifying the abdominal profile to reflect a different BMI, or adjusting the head size to match a specific target. It is also used in this project for joint repositioning, where the method is applied to change the arm and limb positions of the adult male model.

A key limitation of Contour Repositioning when used for mass scaling rather than repositioning is that it can produce sharp deformation at the landmark boundaries. If the target contour defines a significantly different shape from the baseline in a localized area, the transition between the deformed and undeformed regions can create geometric discontinuities that do not reflect the smooth surface of a real human body. This limitation is what motivates the use of Kriging for global shape changes.

Fig. 3
M50-O
Contour Selected.

Fig. 4
Child Model
Contour Selected

Method 3: Kriging Deformation

Kriging is a interpolation method in geostatistics. It was developed in the 1950s by Danie Krige and was formalized into statistical interpolation frameworks by George Matherons in the 1960s. The purpose is that the value at an unknown location can be estimated as a weighted combining the known values at a nearby location, where the weights are determined by the spatial correlation of the data value.

Kriging is used in the following way: users place selected points on the surface of the model and choose an accompanying displacement vector showing the point to where each control point will move. With these specified movements, kriging generates a continuous, smooth displacement across the body mesh based on the spatial positioning of each node to each control point. No node gets displaced in the same direction and amount (as will every other node) that a nearby control point does, kriging produces a smooth distortion of the mesh.

As documented in research on Kriging based HBM morphing published in the Journal of Biomechanical Engineering, this approach is well suited for generating models of different shapes and sizes because it can handle arbitrary numbers of control points and produces deformation fields that preserve element quality better than purely local methods. However, computational cost increases with the number of control points, and element quality degradation can occur with very large deformations or poorly chosen control point configurations.

An important practical constraint in PIPER v1.0.1 is that the number of landmarks (nodes) that can be selected as control points is capped by a hard coded limit in the source code. This limit was encountered during the adult male scaling work and required strategic selection of control points to achieve the desired deformation within the available node count. This is documented as a known limitation of the framework.

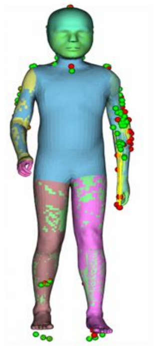


Fig. 5
Unmodified
GHBMC Child 6 Years
3 ‘ 8’’- 45 lbs

Fig. 6
Kriging
GHBMC Child 12 Years
4’ 10’’- 67 lbs

In this project, Kriging was applied to three model families: the child model (scaled from 6 years to ages ranging from 3 to 12 years, generating standing posture versions), the adult male M50-O (modified to represent a higher body mass variant), and both the F5-O and F5-PS female models (scaled to 25th and 95th percentile targets). In all cases, the method produced visually smooth geometry changes without visible mesh discontinuities.

Method 4: Shaping (Beta)

When Shaping, the skeleton acts as the center point and doesn't move with the surface nodes. The nodes will then move the amount the input surface nodes were moved by in response to user manipulation. In effect, shaping a model to an image by picking nodes at the edges and pushing/pulling their outermost points in response to those points on the reference surface, unlike Kriging.

Kriging interpolates a full, seamless motion based on data that it is given about certain points, sculpting doesn't take into account curvature. Any curvature the model develops over the course of shaping is a result of how the node data happens to lay out, the Shaping algorithm itself doesn't try to apply a standard to the curvature at a region boundary, nor does it really care about how far across the surface the motion travels in one single step. Due to its failure to enforce global curvature continuity over a surface, it produces meshing distortions when a portion is changed.

Some reasons mesh can stretch include an improper correction after the deformation and because certain node density doesn't respond in tandem across the entirety of the region affected. The Shaping algorithm was kept in Beta in v1.0.1, only really functional for a 6 year old in PIPER. One particular instance of its usage has been shown here using Shaping to show a mass increase over the 6 year old child from 46 lb to 58 lb while maintaining height. It appears visually convincing, but hasn't been tested against experimental data and in particular, looks distorted near the shoulder region because shaping fails to ensure global smoothness over the resulting surface model.

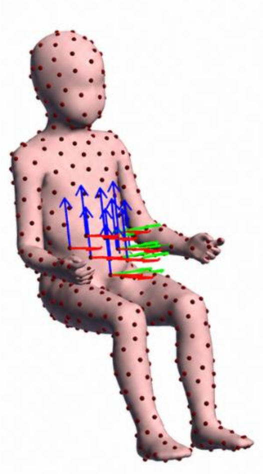


Fig. 1
Original
6-Year-old

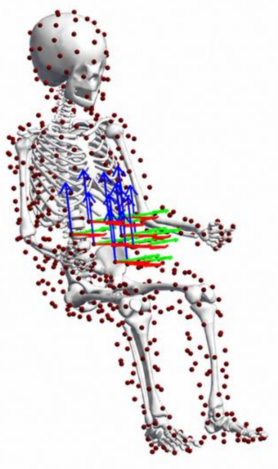


Fig. 2
Original- Skeleton
6-Year-old

Results

Child Age Based Scaling and Repositioned

Child age based scaling gave the highest consistency among ages in this data range. We started with the 6 year old baseline (3 ft 8 in, 46 lbs) and then included ages 3 years (3 ft 1 in, 38 lbs), 8 years (4 ft 0 in, 76 lbs) and 10.5 years via age scaling plus position shifting (4 ft 11 in, 102 lbs). Limb length grew more quickly relative to the head, which appears correct given how the GEBOD model was built and how humans normally develop.

Fig. 1
Modified
3-Year-old
3’1’’ 38 lbs

Fig. 2
Baseline
6-Year-old
3’ 8’’ 46 lbs

Fig. 3
Modified
8-Year-old
4’0’’ 76 lbs

Fig. 4
Repositioned
10 1/2 -Year-old
4’11’’ 102 lbs

It is important to note that this approach maintains the original node connectivity and mesh topology. The mesh alters its shape as the underlying geometry changes, but no elements are added or deleted during the deformation process. Consequently, material assignments and validated contact interfaces remain fully intact.

Child Model Kriging Scaling

Below is a set of generated models ranging from 3 to 12 years using Kriging in a standing posture on a child GHBMC model. Geometrical changes appear smooth without mesh disconnects at each age. A 12 year old model of height 4 ft 10 in (147 cm) and mass 67 lbs (30 kg) increases proportionally to the 3 year old model (2 ft 10 in (86 cm), 29 lbs (13 kg)). The colors visible in the renders are parts defined by the GHBMC mesh and aren't geometrical problems.

The only problem encountered during the Kriging phase was a maximum of 255 nodes being allowed by the PIPER program v1.0.1. The child GHBMC model is intricate, as it consists of 45 bone components, which in themselves possess substantial complexity within the body. Picking suitable nodes so that all bones and soft tissue components can be correctly manipulated within the limits of the allowed node counts requires considerable tweaking to find the correct distribution. The final configuration has about 500 nodes used for manipulation of all bones and surrounding tissue.

Fig. 1
Modified
3-Year-old
3'1" 38 lbs

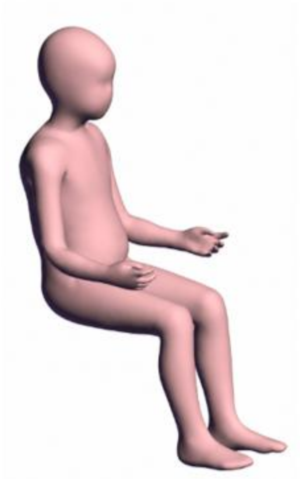
Fig. 2
Baseline
6-Year-old
3' 8" 46 lbs

Fig. 3
Modified
9-Year-old
4' 2" 83 lbs

Fig. 4
Modified
12-Year-old
5' 2" 120 lbs

Fig. 1
Baseline
6-Year-old
3' 8" 46 lbs

Fig. 2
Modified
6-Year-old
3' 8" 58 lbs



Adult Male Kriging Scaling

An adult M50-O model was first transformed with two operations. We used Contour Repositioning to reposition the arms from an extended position into a driver's arm posture because it makes sense to put a male model into a car driver simulation setup, to accomplish this, we selected the arm geometry and used an target contour from the driver joint angles to repose the arms. The resulting geometry had the arms posed to drive but left the geometry of the torso, head and legs intact.

Next, Kriging was performed on the body mass to transition the model's 161 lb weight (M50-O) to 190 lb weight (M29-O). Kriging's control points were spread over the torso, abdomen and limb external surfaces, with displacement vectors pointed away from the model surface, increasing the outside volume. The output of the Kriging step shows the expected increase in body mass in the form of a deeper torso/abdomen and no sharp features on the model.

By performing both operations, we end up with a combined M29-O with repositioned arms, demonstrating PIPER operations can be chained together to form a new, complex modification result.


Fig.1
Baseline- Arms
M-50-0
5'9" 161 lbs


Fig.2
Baseline-
Repositioned
M-50-0
5'9" 161 lbs


Fig.3
Modified
M-29--0
5'9" 190 lbs


Fig.4
Modified- Arms
Repositioned
M-29--0
5'9" 190 lbs

Female Model Results Kriging Scale

We produced a total of three F5 based females that represent the 5th, 25th and 95th - percentile females in terms of mass (respectively 4 ft 11 in, 109 lbs, 5 ft 1 in, 137 lbs and 5 ft 9 in, 263 lbs). Kriging interpolation results using the F5 model as a base and two separate scaling target points one representing a 25th percentile female (5 ft 1 in tall, 137 lbs) and one representing a 95th - percentile female (5 ft 9 in tall, 263 lbs) will be produced next. Kriging results tend to smooth out variations, but note that both the occupant (seated) version and the pedestrian (standing) version of each female type will be produced. Notice the increase in body depth of the F95 model about the baseline F5 model in the 95th percentile. Both the F5 and F95 model will be modeled in both occupant position (seated) and in pedestrian position (standing) posture.

Figure below compares F95 females against F5 female. Several observations can be made comparing these. First, Kriging smoothly interpolates results, compare the curve along the chest of F5 with that of the F95 model. Additionally, a significant increase in torso depth/volume is seen comparing F95 females with the F5 female, as is necessary for the increased body volume of the F95 female. The F5 female occupies sitting and standing posture and Kriging can smoothly map to desired changes in anthropometrics across both configurations, each F5 female used can be a match between the 5th percentile F5 seated occupant model with a F5 standing pedestrian model and likewise between modified 25th - percentile females or modified 95th - percentile females.

Fig.1
Baseline
F-5-O
4'11" 109 lbs

Fig.2
Modified
F-25-O
5'1" 137 lbs

Fig.3
Modified
F-95-O
5'9" 263 lbss

Fig.1.1
Baseline
F-5-PS
4'11" 109 lbs

Fig.2.1
Modified
F-25-PS
5'1" 137 lbs

Fig.3.1
Modified
F-95-PS
5'9" 263 lbs

Discussion

A major finding of this project is that the most suitable scaling method depends greatly on what you're scaling, your baseline and how accurate the geometry must be geometrically. Given all of our findings from this project, the following figure is our recommended approach for using the methods we presented:

Method	Recommended Use Case
Child Age Based Scaling	Uses growth charts to resize a child model as they age. Works great for kids because bodies change predictably with age. Useless for adults since adults don't follow growth curves.
Contour Repositioning	Best used for repositioning specific body parts rather than full body scaling. May also be applied for mass scaling only in the entire body.
Kriging Deformation	The most flexible option. it smoothly stretches/reshapes everything around them. Good for changing overall height or weight.
Shaping (Beta)	Best suited for fine-tuning local shape details that other methods can't precisely capture. Requires careful handling to avoid mesh distortion or discontinuities at region boundaries.

No single method works for every model depends on what you're changing in the model. Choosing what method depends on the model

Age-Based Scaling: Uses growth charts is ideal for child HBMs since bodies change predictably with age. Not applicable to adults. Contour Repositioning: Best for adjusting specific body regions rather than full-body rescaling. Can handle mass-only scaling globally. Kriging Scaling: Most flexible option and best method it creates smooth model it can be making changes across the whole model or just specific regions of the body. Best for overall use , height or weight changes. Shape Scaling**:** Fine tunes specific regions well compared to other methods. Also, it is still in beta and needs to be update.

Limitations

Legacy Software Status

PIPER v1.0.1 is no longer actively maintained. The PIPER project concluded its European Commission funding cycle in 2017, and while the software remains available as opensource, no further development is planned under the current project structure. This has several practical consequences for research built on PIPER.

Furthermore, there won't be any fixing of existing software bugs or limitations. In particular, the number of allowed control points in the Kriging module is hardcoded in the source, a simple patch to remove or raise that'd suffice, but no such patch will come into existence, given that no one appears to be maintaining it now. As such, anyone working within the confines of that particular algorithm would either need to take it into their own hands to patch the code base or alter the technique in which they choose and assign the location of the control points.

Biomechanical Validation

The most significant scientific limitation of this project is that the modified HBMs have not been validated against experimental impact corridor data. Biomechanical validation, in which a simulated impact is compared against the response of a post-mortem human subject (PMHS) or other experimental standard under the same loading conditions, is the standard by which the scientific community assesses whether an HBM can be trusted to make accurate injury predictions.

Without validation, the modified models can demonstrate geometric plausibility but cannot be used with confidence for quantitative injury risk prediction. The Kriging and Age-Based Scaling methods preserve the material properties of the baseline, which is a reasonable approximation, but whether the biomechanical response of the modified model matches experimental data for the target anthropometry is an open question that this project cannot answer.

Validation is identified as the single most critical next step for this work. Without it, the modified models are most appropriately used for qualitative and comparative analyses rather than for absolute injury risk assessment.

Node/ Landmark Limitations

As discussed in the methodology section, PIPER v1.0.1 imposes a hard limit on the number of nodes that can be selected as control points in the Kriging module. This limit is embedded in the source code rather than being a user-configurable parameter. For models with complex internal anatomy like the GHBMC M50-O, which includes detailed skeletal structure, organ geometry, and soft tissue layers, reaching adequate coverage of the model surface within the node count limit requires careful and sometimes iterative control point selection.

In practice, this limitation was worked around by using a strategic sampling approach: control points were distributed to prioritize the outer surface geometry, the major joints, and the anatomical landmarks most relevant to the target modification. Internal anatomy was relied upon to deform correctly through interpolation from the surface control points. For moderate deformations, this approach produced acceptable results. For large deformations or highly localized shape changes, the limitation becomes more constraining.

Shaping Module Beta

As a note, it is still in beta testing that module in PIPER 1.0.1. It appears it really doesn't work on anything but child Piper Models. When I used it with my GHBMC adult man, the mesh twisted into unrecognizable garbage in almost every situation. I also agree with you there should be Jacobian fixes in. I imagine that the main reason the whole module is still Beta is that it lacks those constraints. But even the closest node approach to mesh generation that we got was problematic and it didn't make any effort toward node contiguity.

With shaping, there simply isn't a mesh generation algorithm at all, only a mesh moving algorithm with no attempt to add mesh corrections after deformation, such as those required by Jacobians and also, it does not care about what order you add Nodes into the mesh so long as it can grab nodes within the proximity defined.

Conclusion

The goal of this project was to develop and showcase a methodology for modifying validated GHBMC Human Body Models to approximate diverse anthropometric targets using the PIPER v1.0.1 framework. The following conclusions can be made on the basis of these findings. PIPER based scaling is a robust approach for scaling models. Each of the five base GHBMC models could be successfully modified to accurately represent target anthropometry, thereby demonstrating the feasibility of this technique for anthropometric diversity within existing HBM databases. The PIPER framework supports four distinct methods for model alteration, each tailored to specific requirements. For pediatric models, the biomechanically sound approach is Child Age - Based Scaling. For models representing adults and children alike, Kriging offers the highest flexibility and the widest applicability. Contour Repositioning is most useful when the intention is to adjust shape or pose in a limited manner. Shaping, meanwhile, is an experimental technique that'd require additional research and development.

The modification workflow (as opposed to the rebuilding process) offers a viable path forward. Modifications to an existing, validated model can typically be made using PIPER in hours to days, in contrast, the construction of a brand - new model typically requires weeks, months or years. The resulting geometry is smooth and the materials property validation of the source model is preserved through the modification process. Export capabilities exist for numerous simulation platforms. Every one of the modified models generated by this project could be successfully exported as an LS - DYNA, Abaqus and HyperMesh model ready for immediate incorporation into crash simulation processes.

Crash safety inequality is a real world problem that has ethical as well as technical implications. Currently, major differences exist in how often models in the existing HBM libraries represent men than women. This demographic disparity means that there's a higher rate of injury sustained by females in various crash types As part of the pursuit of more broadly representative and ethically accountable safety, HBM libraries need to incorporate more anthropometric variations that mirror the occupant demographics in the general public.

Future Work

Biomechanical Validation

The most critical next step is validating the modified HBMs against experimental impact corridor data. For the child models, this would involve comparing simulation outputs against test data for children of corresponding ages and sizes. For the female models, validation against chest impact, thoracic belt loading, and lateral impact corridor data would establish the accuracy of the Kriging modified geometry for injury prediction. This validation work would require access to experimental datasets and to a solver environment (LS-DYNA or Abaqus) capable of running full crash simulations.

Shape Tool Integration

With computing resources and software development investment, incorporating the PIPER Shaping module for locus-specific modifications that cannot be achieved through Kriging or Contour methods would expand the range of anthropometric targets accessible to this workflow. Resolving the mesh quality issues associated with the Shaping method is a tractable engineering problem, and doing so would make the tool useful beyond its current Beta limitation to the child model only.

Population-Scale HBM Libraries

The ultimate goal of this work is to enable population-scale crash safety analysis. Extending the workflow to systematically generate HBM libraries spanning the full age, sex, and BMI spectrum relevant to the US driving population would enable the kind of large-sample simulation studies that can reveal demographic specific injury patterns and drive the design of more equitable restraint systems. This could be achieved through a combination of Kriging-based morphing from validated baselines and statistical shape model guidance for consistent sampling of the anthropometric space.

Automation Pipeline

The current PIPER workflow requires manual user interaction at several steps, including control point selection, target file preparation, and export configuration. Automating this pipeline through PIPER's Python scripting interface would enable high throughput generation of diverse HBM families. Automated pipelines could generate batches of models for crash simulation studies, statistical restraint system optimization, or regulatory compliance analysis across diverse population segments.

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