automotive CAE GRAND CHALLENGE

Human Body Models customization by advanced mesh morphing: parametric THUMS

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A brief introduction to RBF Morph

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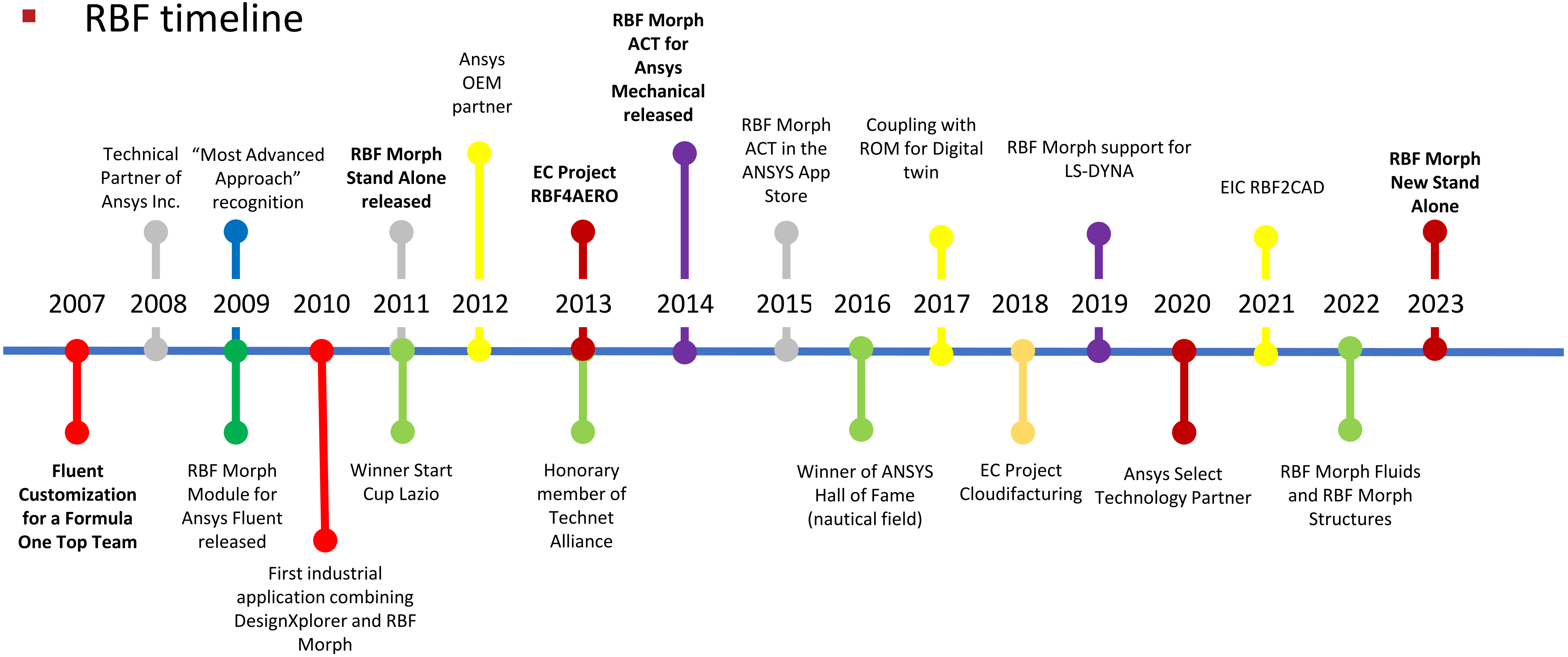
- RBF timeline



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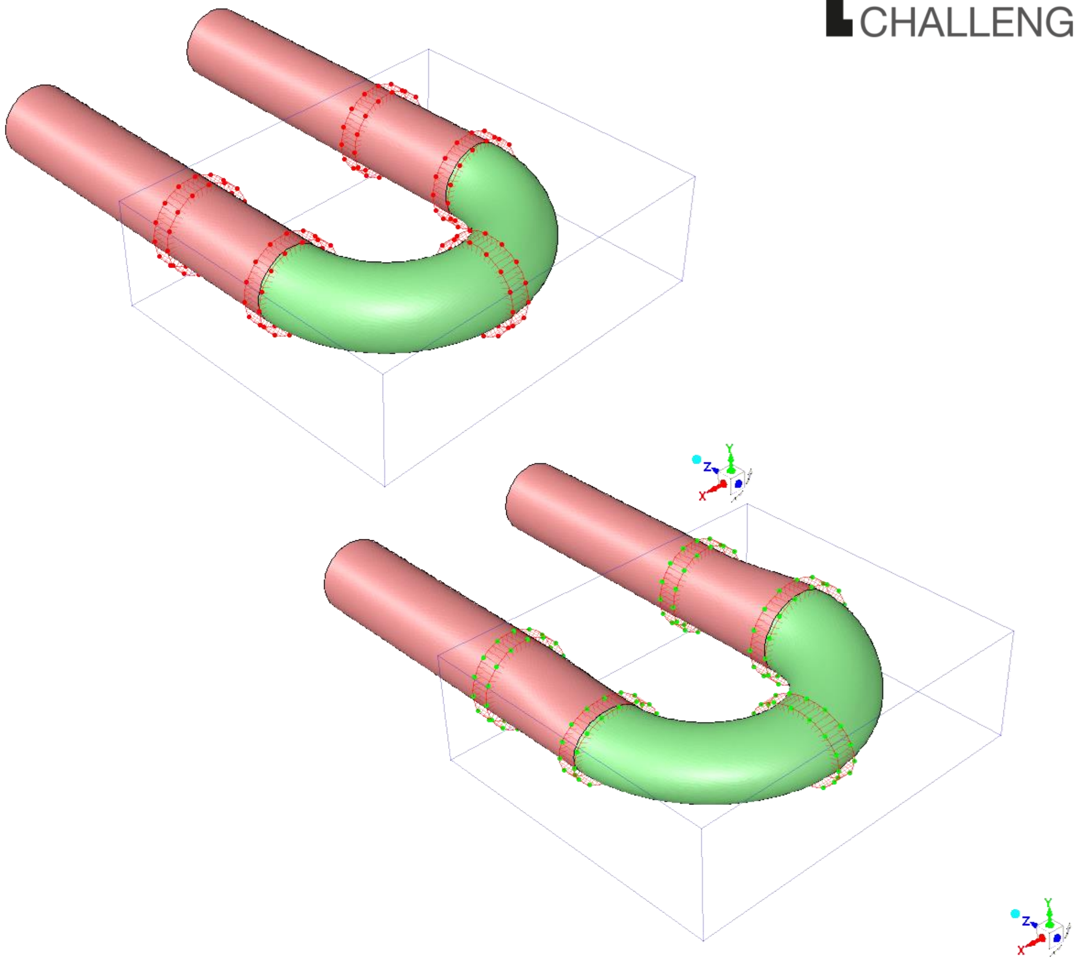
Shape parameterization strategy

- Geometric parameterization by **mesh morphing**
- The principle is to take the control on a set of point and to transfer the deformation to the whole mesh
- A **new shape** of the CAE model **ready to run**
  - for structural analysis in the FEA solver
  - for flow analysis in the CFD solver



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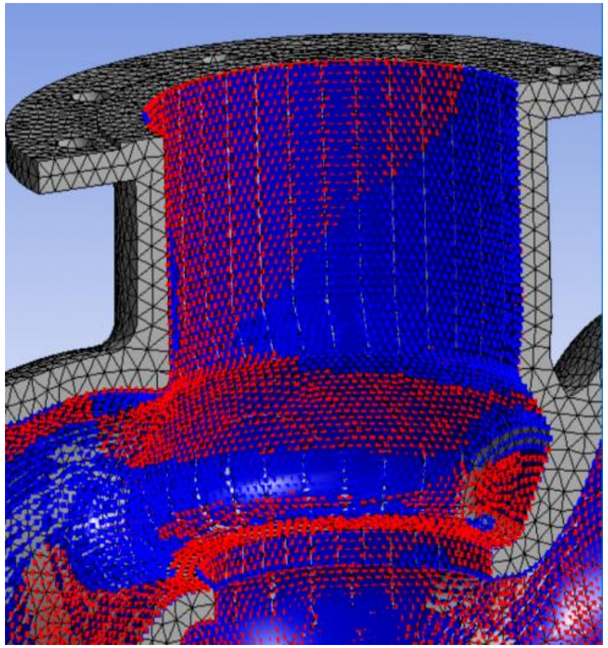
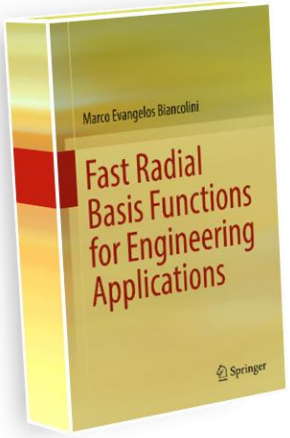
Radial Basis Functions mesh **Morphing**

- We adopt **Radial Basis Functions** (RBF) to drive mesh morphing (smoothing) from a list of source points and their displacements
  - Surface shape changes
  - Volume mesh smoothing
- RBF are recognized to be one of the **best mathematical tool** for mesh morphing





$$
\begin{cases}
s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi(\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\|) \\
s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi(\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\|) \\
s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi(\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\|)
\end{cases}
$$

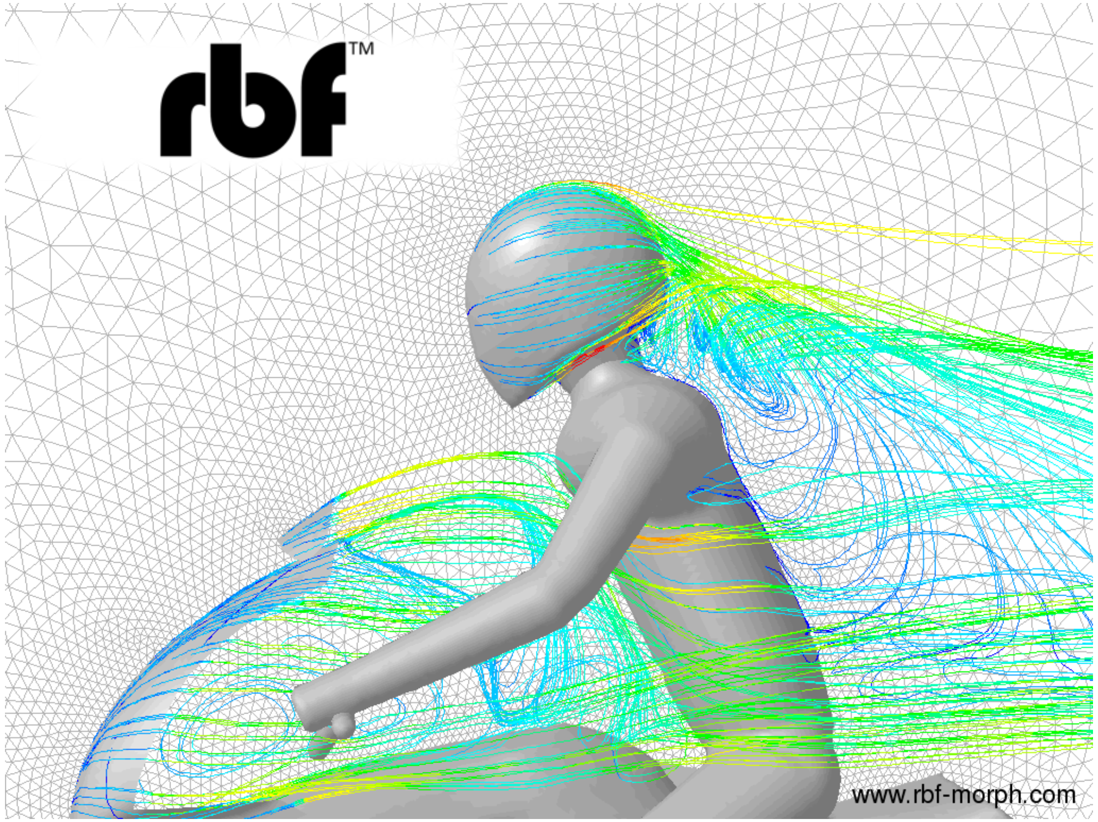
Radial Basis Functions mesh **Morphing**

www.rbf-morph.com

- No re-meshing
- Can handle any kind of mesh
- Can be integrated in the CAE solver (FEM/CFD/FSI)
- Highly parallelizable
- Robust process
- The same mesh topology is preserved (adjoint/ROM)
- CAD morphing (iso-brep)

We make CAE models parametric

- RBF Morph makes the CAE model **parametric**
- Shape parameters are driven by **an orchestrator**
- Shape parameters can be used to generate snapshots for real time **Digital Twins (ROM/AI)**



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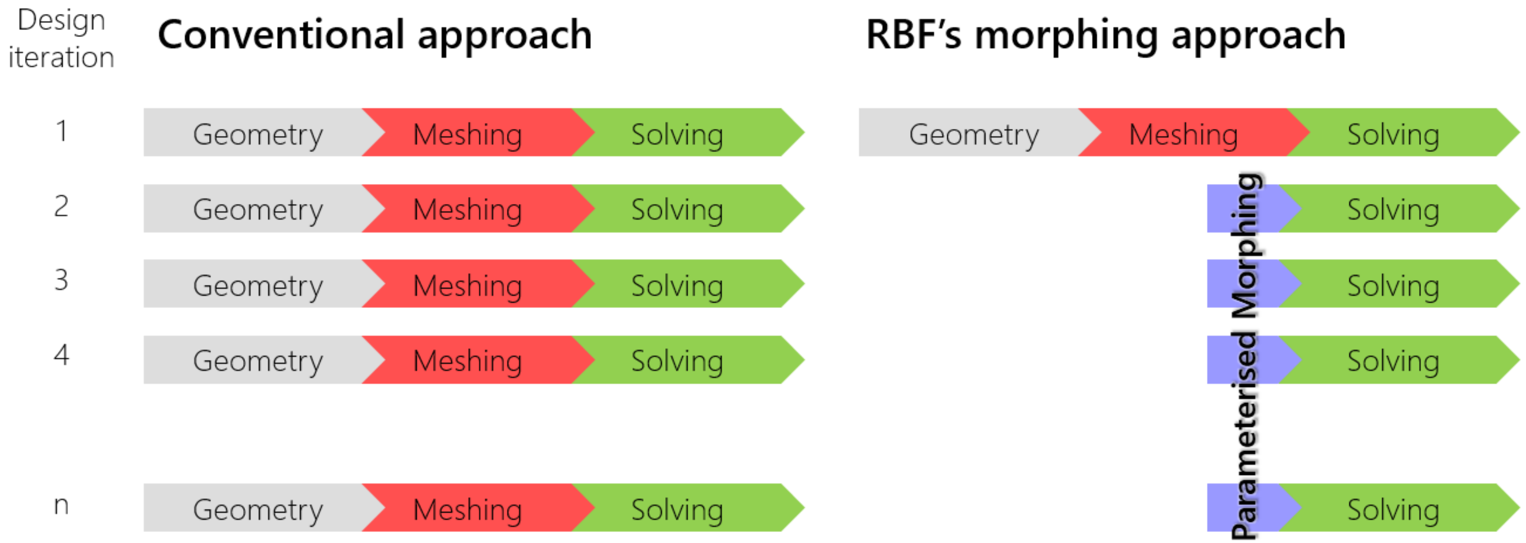
We make CAE models parametric

- Morphing is a **key enabler** for optimization and Digital Twins
- The turnaround time of the optimization is usually reduced by a **factor five** (weeks becomes days)



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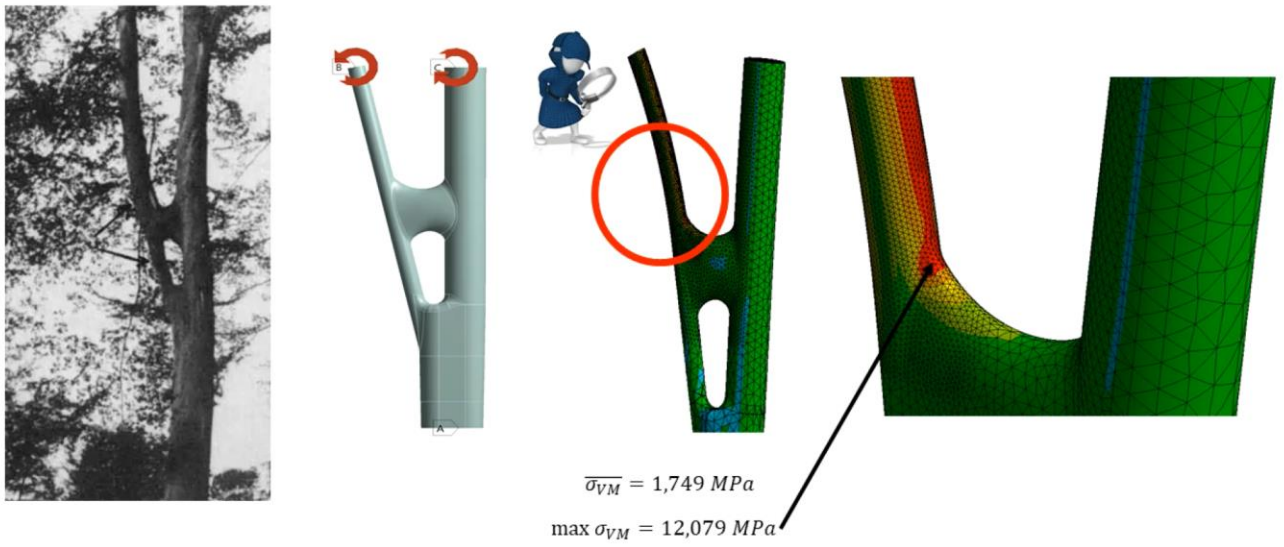
Parameter-free shape optimization

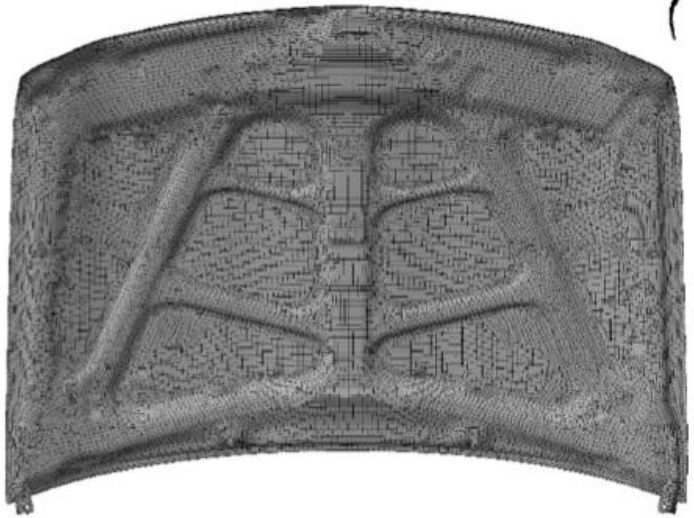
- The new shape can be guided by the CAE solution itself (organic shapes)
  - Coupled with the **CFD adjoint** solver
  - **BGM** (Biological Growth Method) optimizer in FEA solver



Use case: reusing the LS-DYNA model of a different car

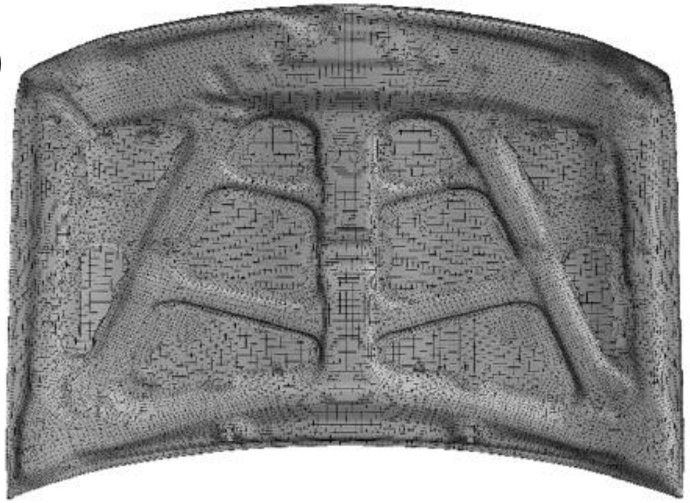
Honda Accord starting mesh

Morphing onto the style (parameter-free)



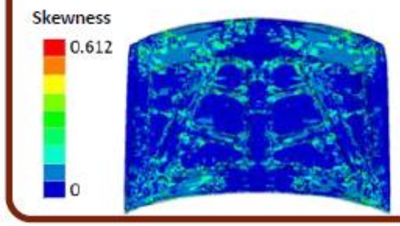
Honda Accord mesh matching the Chevrolet Silverado shape

Morphing onto the performances (parameter-based)

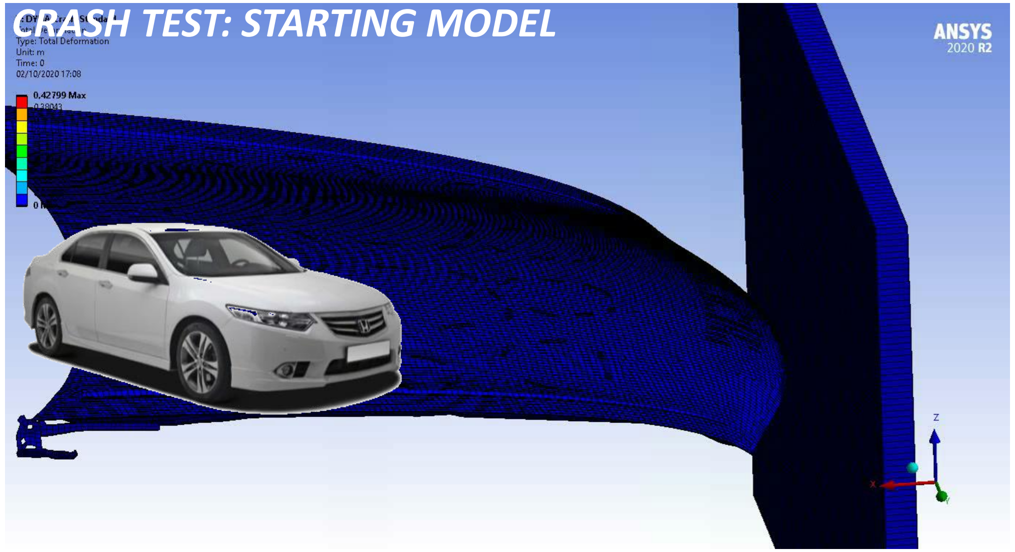


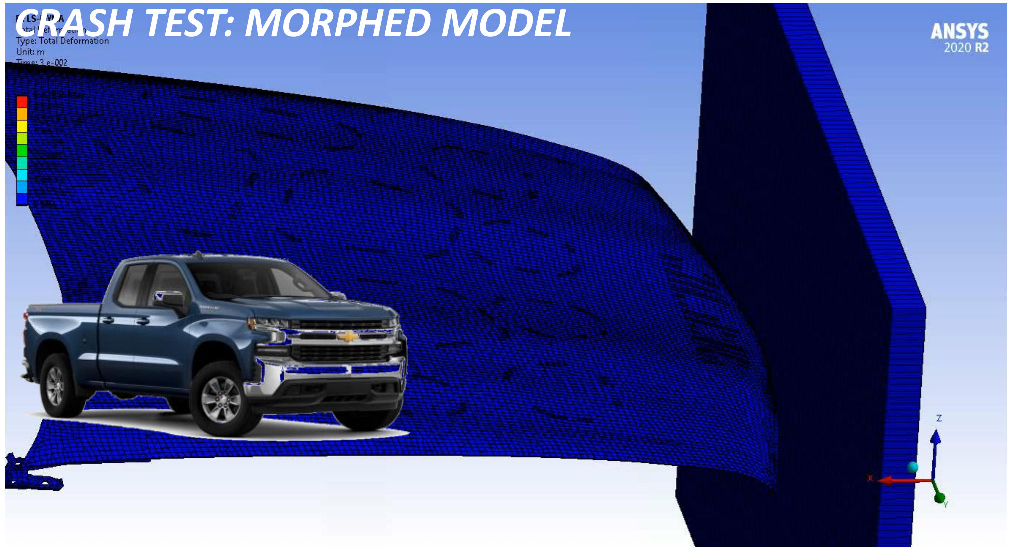
Honda Accord mesh matching the Chevrolet Silverado shape and crashworthiness needs

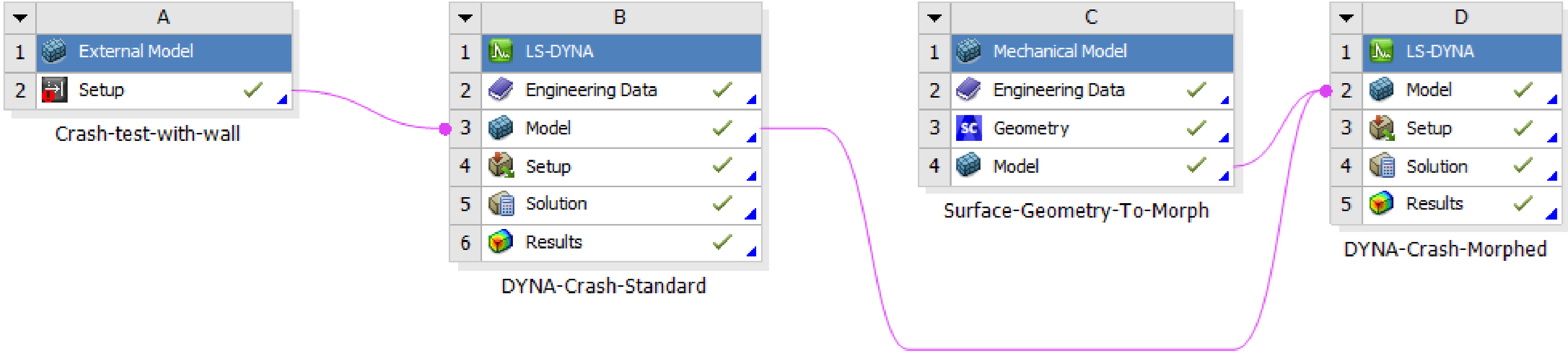
Quality check



Use case: reusing the LS-DYNA model of a different car







Ansys LS-DYNA

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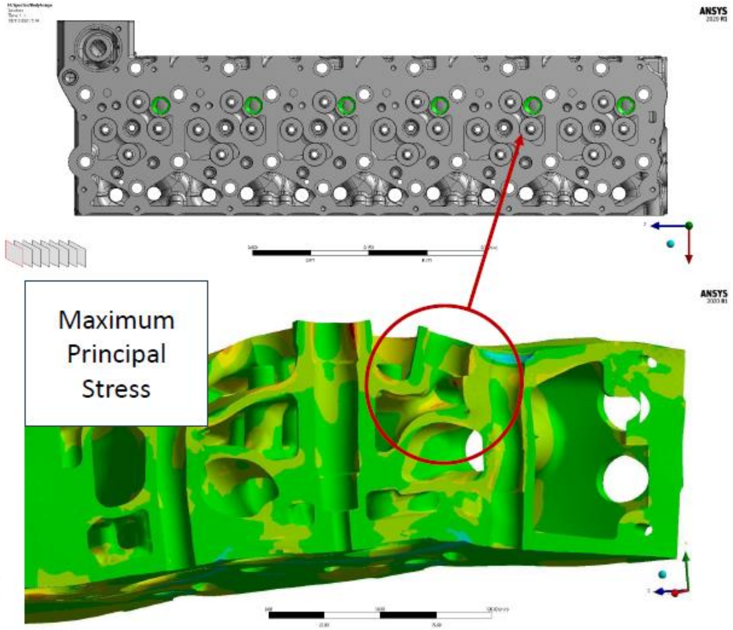
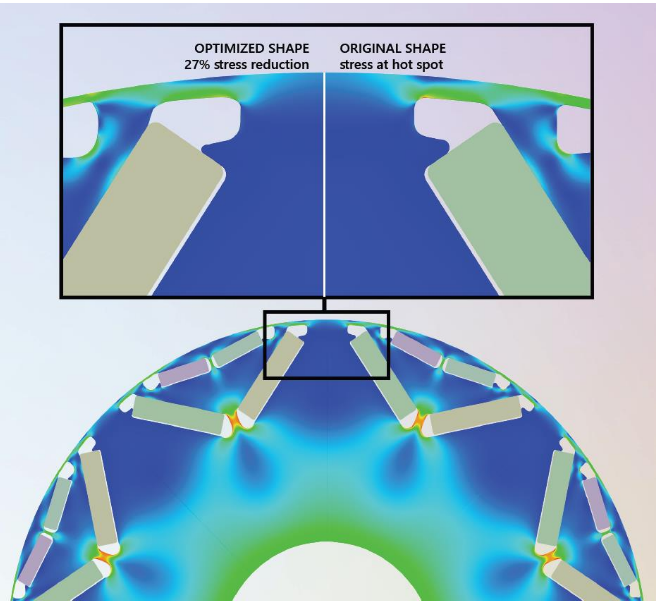
Use case: multi-physics optimization of a powertrain

- Powertrain optimization using the **BGM method** to improve the durability of an internal combustion engine and of an electric motor
  - Thermal engine: mitigation of a hotspot in the engine head in a district close to the exhaust valve
  - Multi-physics analysis of the intake and exhaust flows, the liquid coolant flow and the thermos-structural analysis
  - 15% reduction of the hot-spot stress





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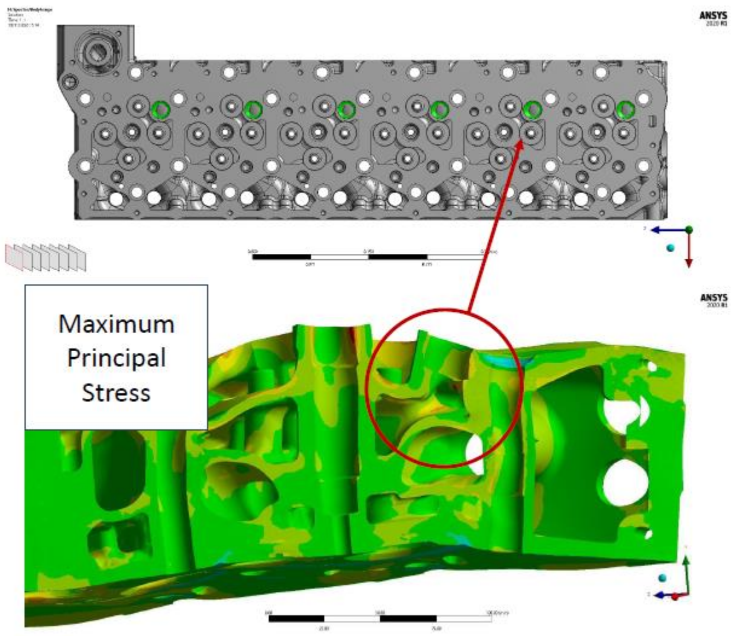
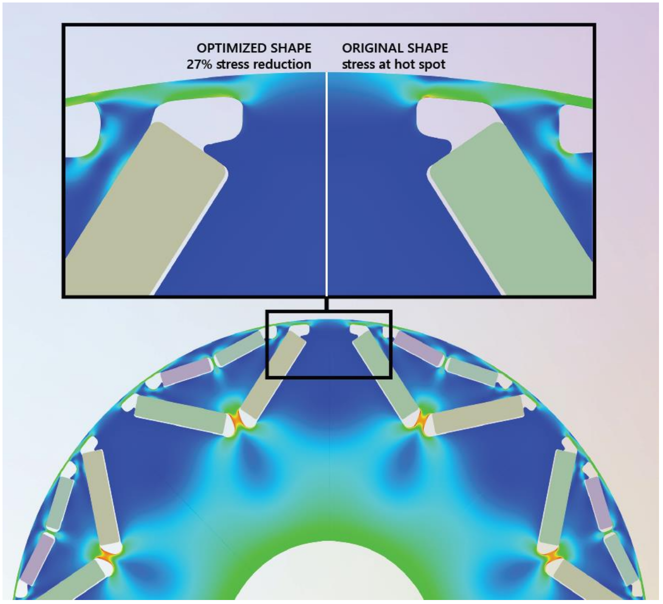
Use case: multi-physics optimization of a powertrain

- Powertrain optimization using the **BGM method** to improve the durability of an internal combustion engine and of an electric motor
  - The same BGM approach is used for the rotor of an electric motor with the structural analysis coupled with an EM one
  - The shape of the pocket is changed getting a 27% stress reduction





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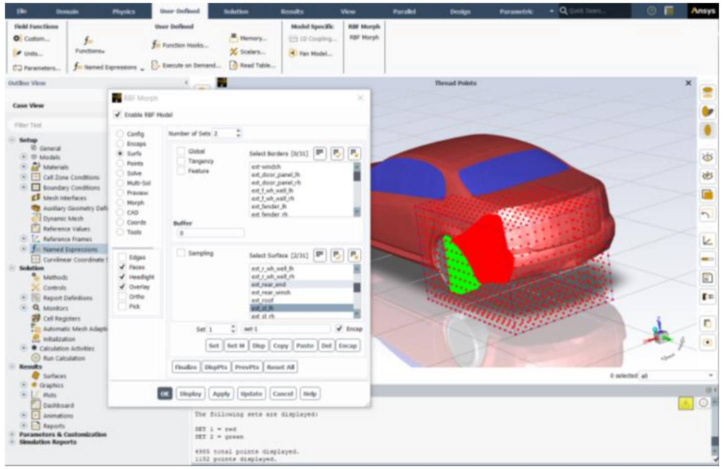
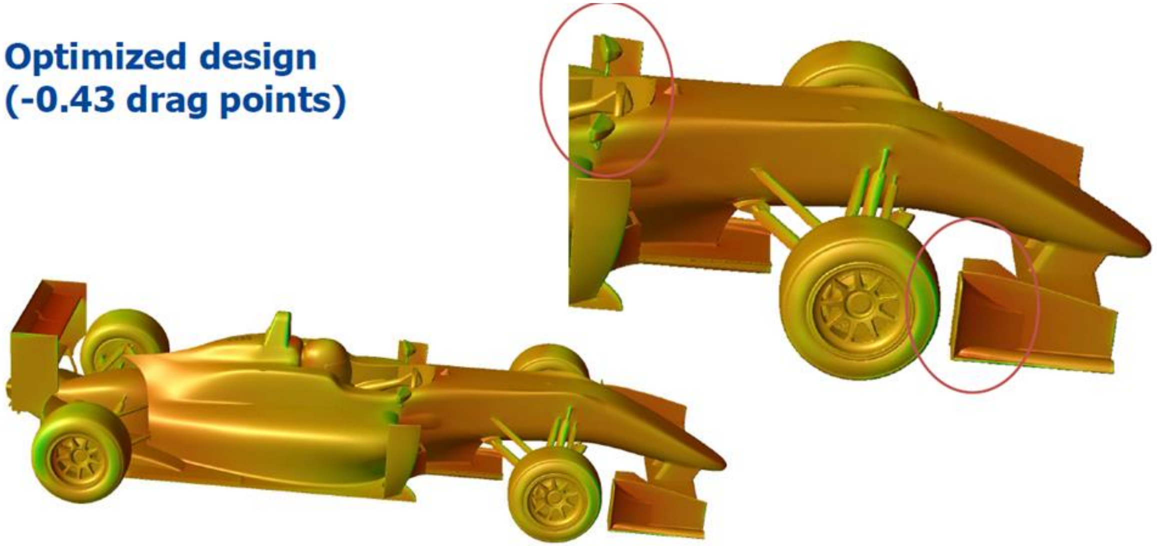
Use case: aerodynamic shape optimization

- Parametric mesh morphing can be implemented in the **automotive and motorsport fields** for aerodynamic shape optimization
  - Car shape refinement for aerodynamics improvement, can be implemented in interactive design
  - Formula 3 vehicle drag reduction, through shape optimization



Optimized design
(-0.43 drag points)



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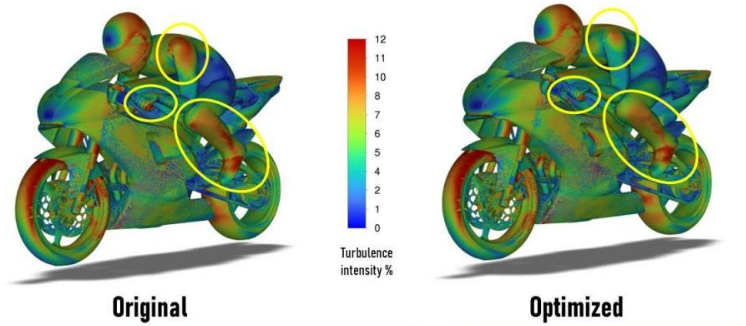
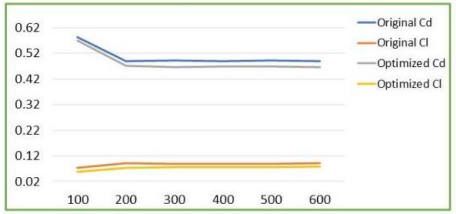
Use case: motorbike aerodynamics development in VR

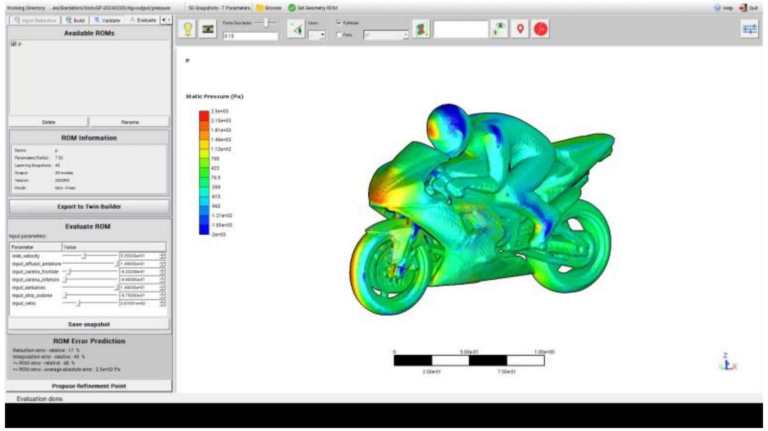
- Motorbike **aerodynamic optimization** and **reduced-order model building** for virtual reality
  - Mesh morphing parametric shape optimization in the selected interest area
  - Drag coefficient reduction compared to the original shape
  - Parametric morphing enables reduced-order model building for interactive visualization





Gains

- 3.5% in drag coefficient C_d
- 23% in lift coefficient C_l



Parametric THUMS

Parametric THUMS: Introduction

- Vehicle safety: injury predictions
- Injury prediction tools
- Crash tests: **ATDs** (Anthropometric test devices)

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Parametric THUMS: Introduction

- Vehicle safety: injury predictions
- Injury prediction tools
- Crash tests: **HBMs** (Human body Models)

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HBMs vs ATDs

- ✓ Complete Anatomy→ Accuracy
- ✓ Omnidirectionality → Flexible usage
- ⚠ Small number of shapes available

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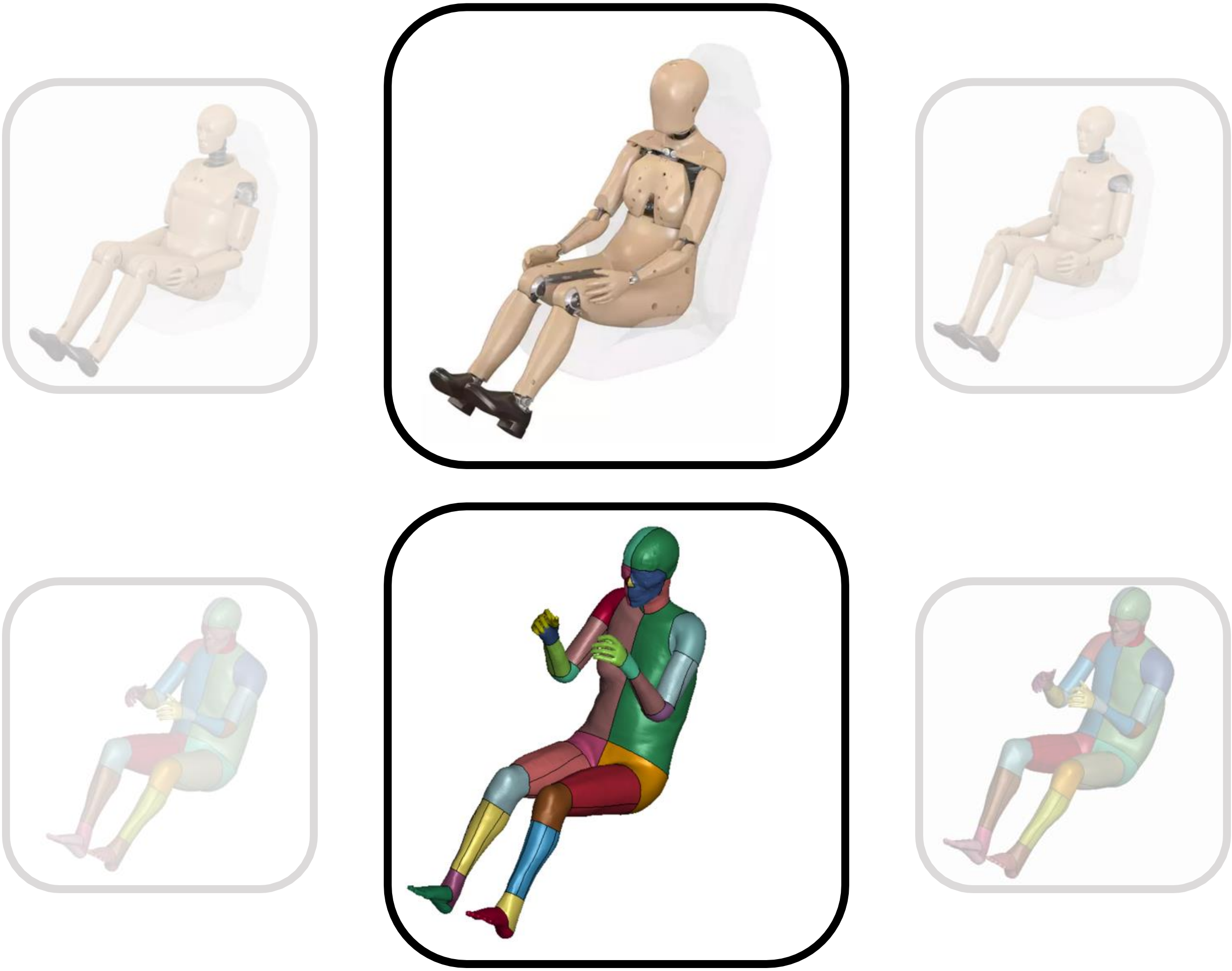
Small number of shape



Small size adult female

- Shape corresponding to the 5^{th} statistical anthropometric percentile

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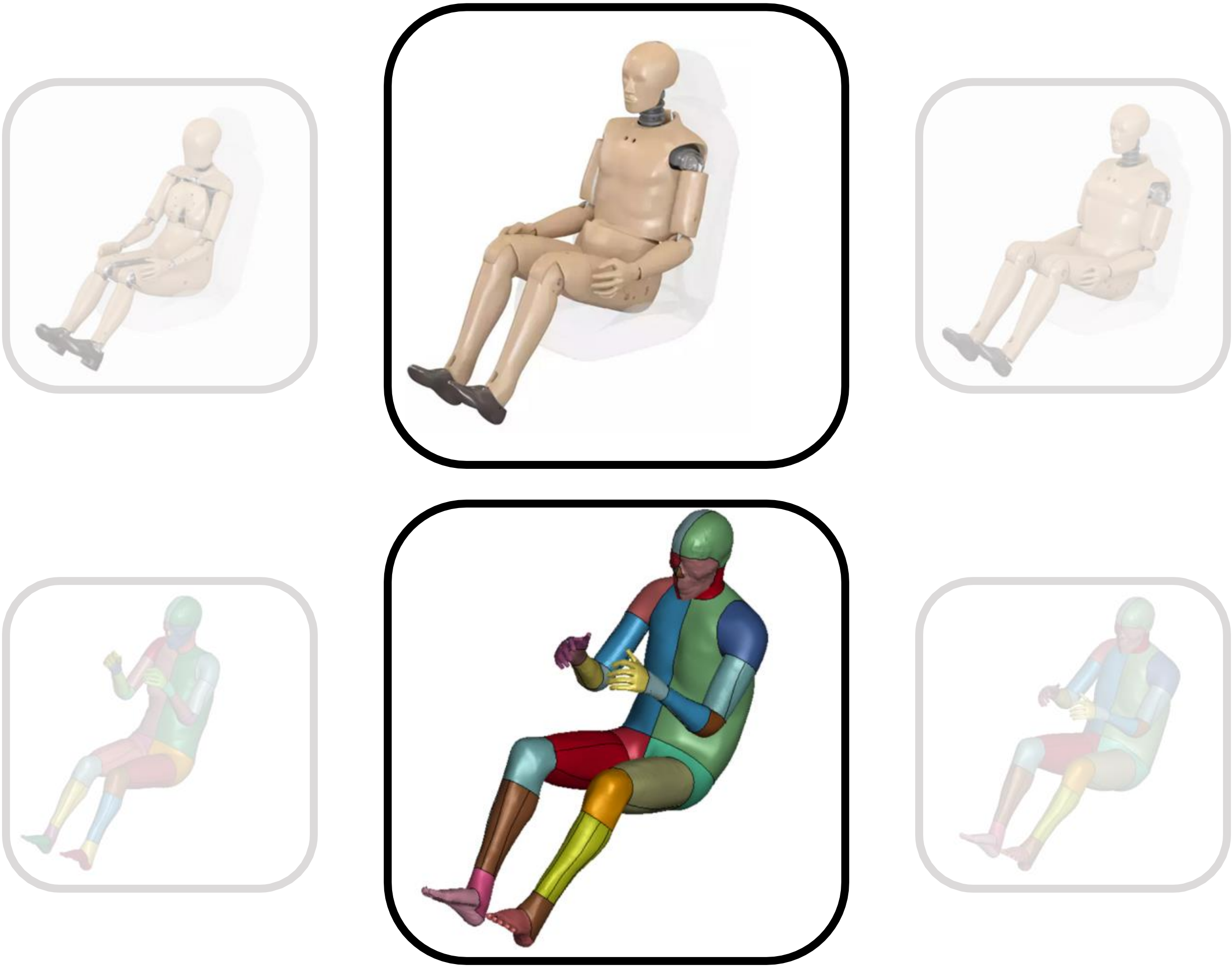
Small number of shape



Middle size adult male

- Shape corresponding to the 50^{th} statistical anthropometric percentile

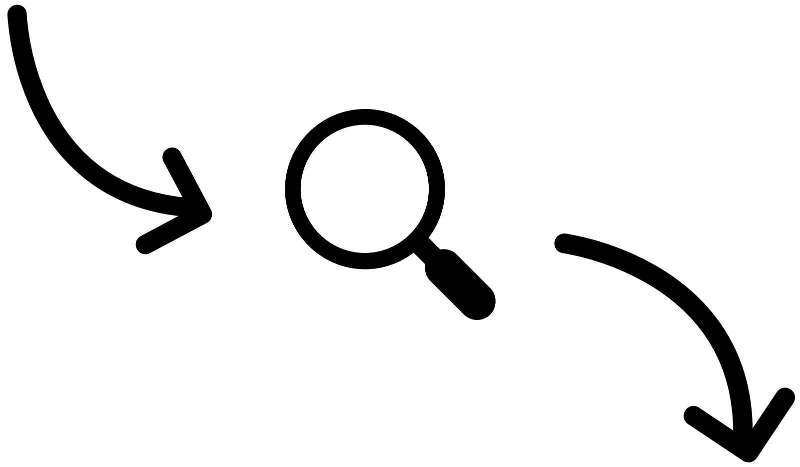
Small number of shape

Large size adult male

- Shape corresponding to the 95^{th} statistical anthropometric percentile

Small range of shape

- In the development of HBMs, most anthropometric shapes have remained unexplored



Human Body Models customization

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Total Human Model for Safety: THUMS

- Developed by **TOYOTA**
  - Developed **since 1997**
  - Available as **open source** since **2021**
- Advanced features

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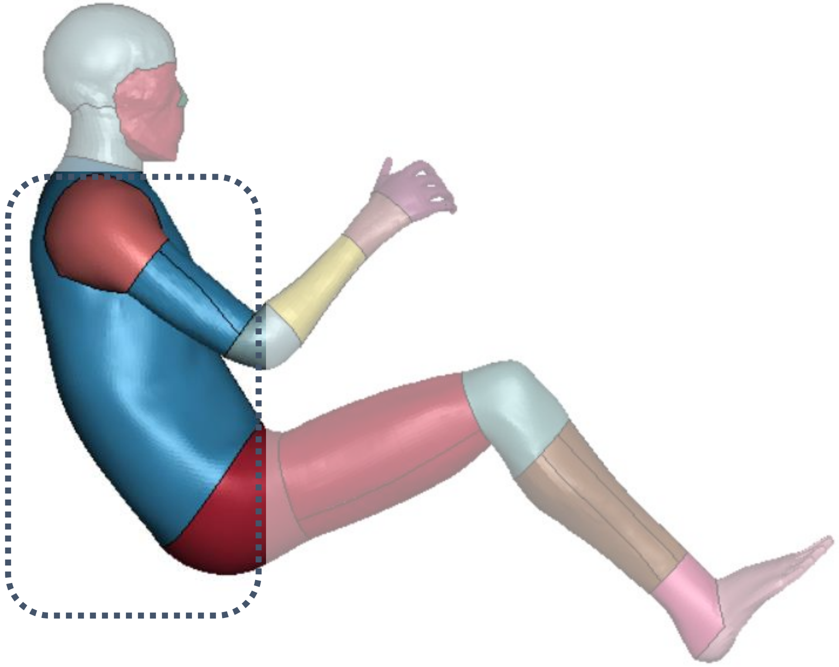
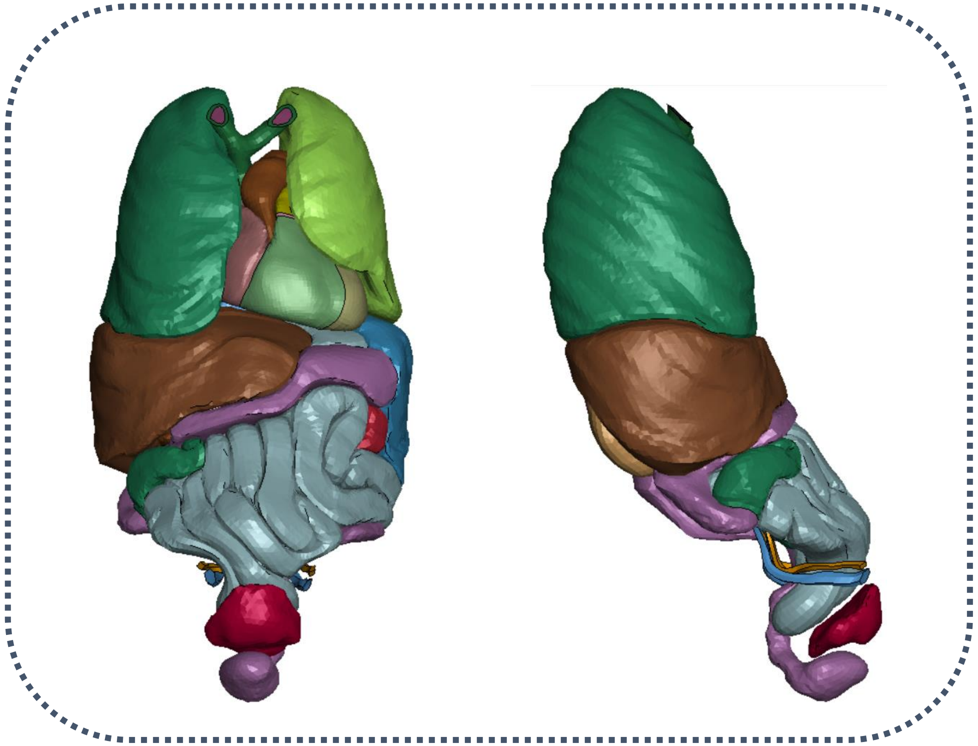
Total Human Model for Safety: THUMS

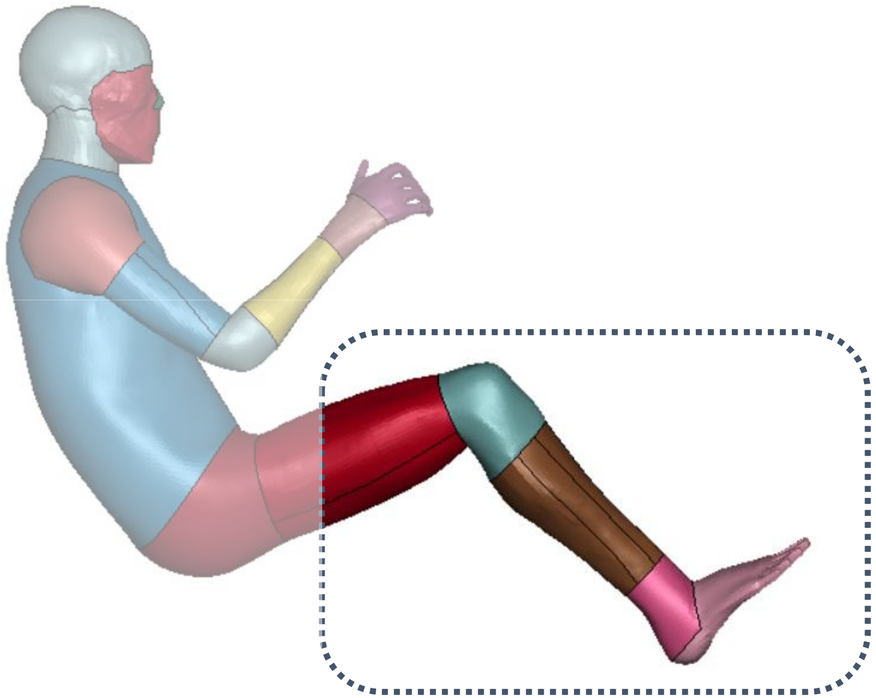
- **Internal organs** geometry extremely detailed

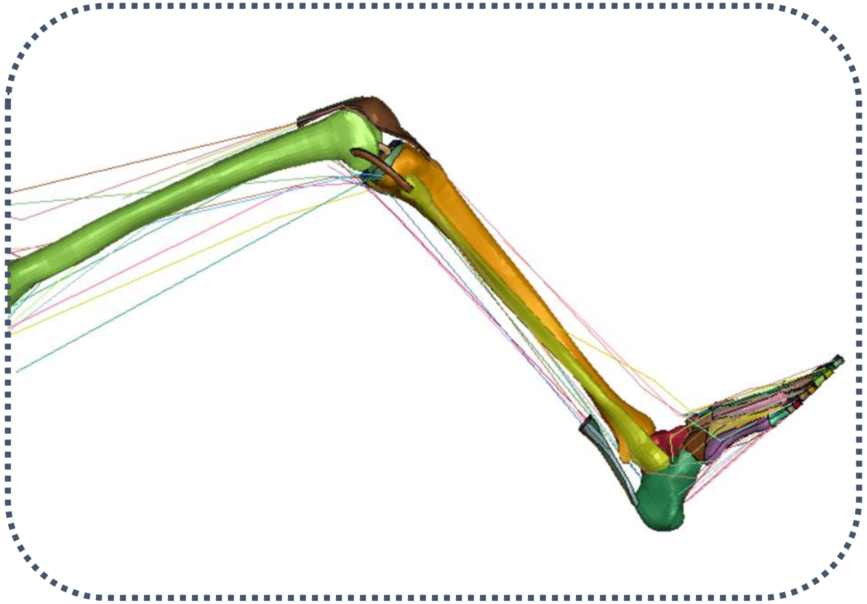




Total Human Model for Safety: THUMS

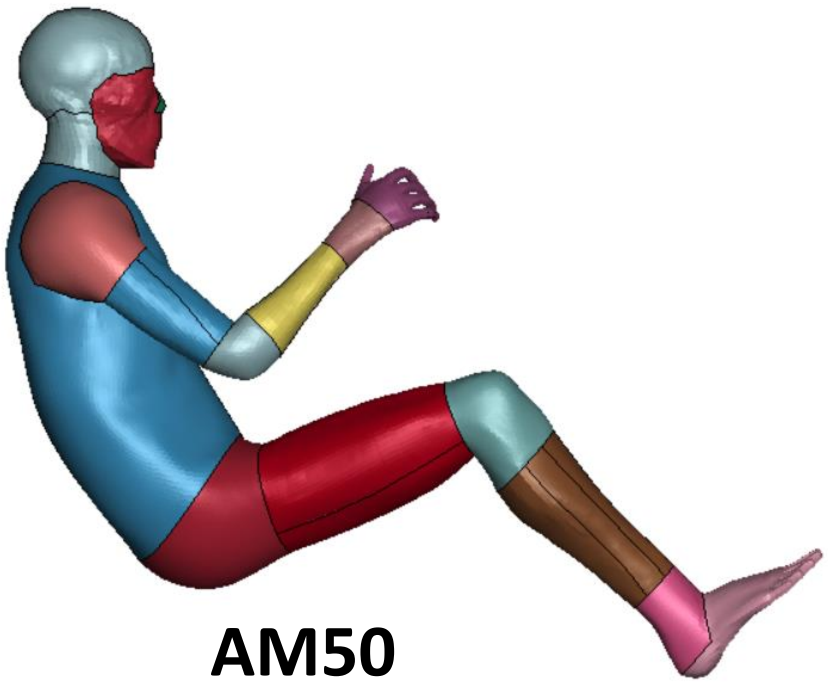
- **Complete modeling of muscolar function** through one-dimensional elements activated by feedback controllers



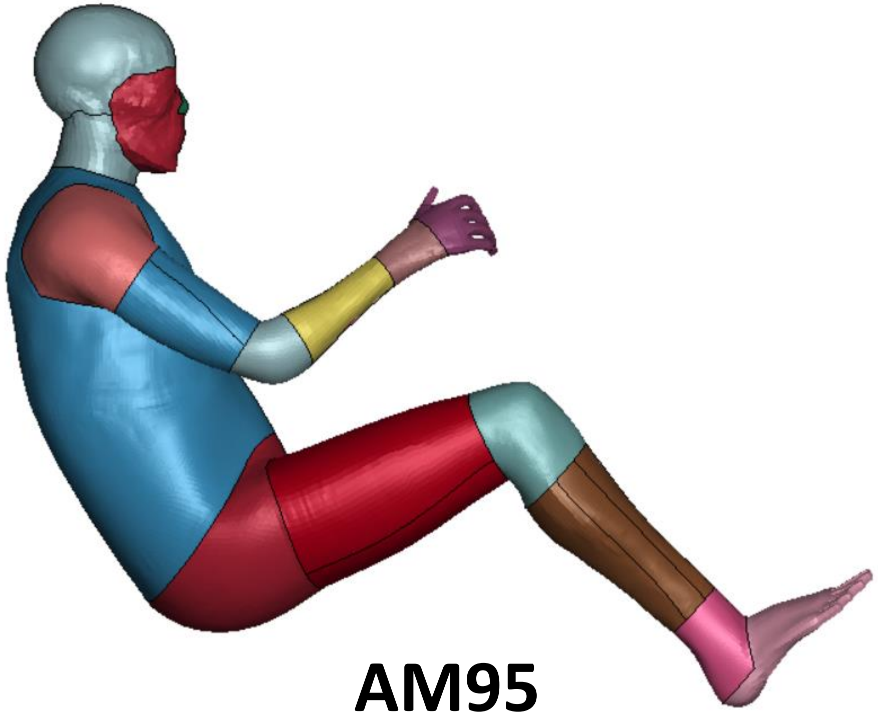


Total Human Model for Safety:

- Unique shapes available for male models: 50^{th} and 95^{th} statistical anthopometric percentile



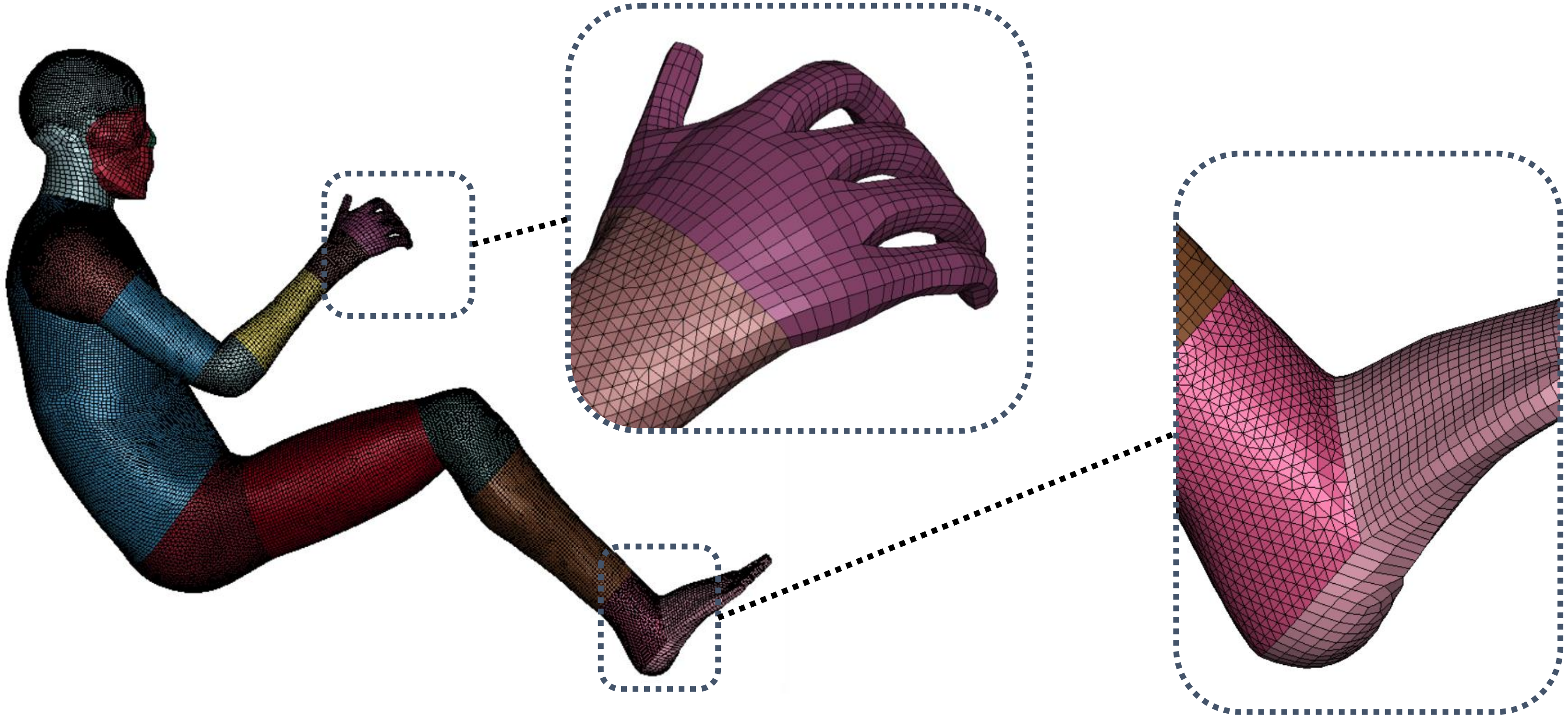
AM50



AM95

Total Human Model for Safety: THUMS

- **Mesh** composed of over **2 milion elements**



Objective

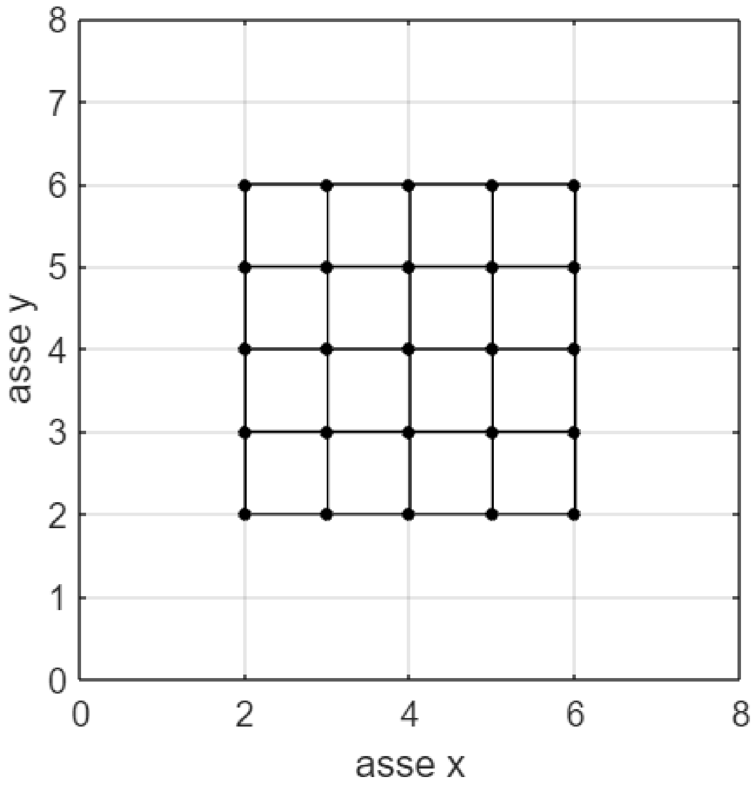
- **Define** a method to create **THUMS** corresponding to the **generic percentile**

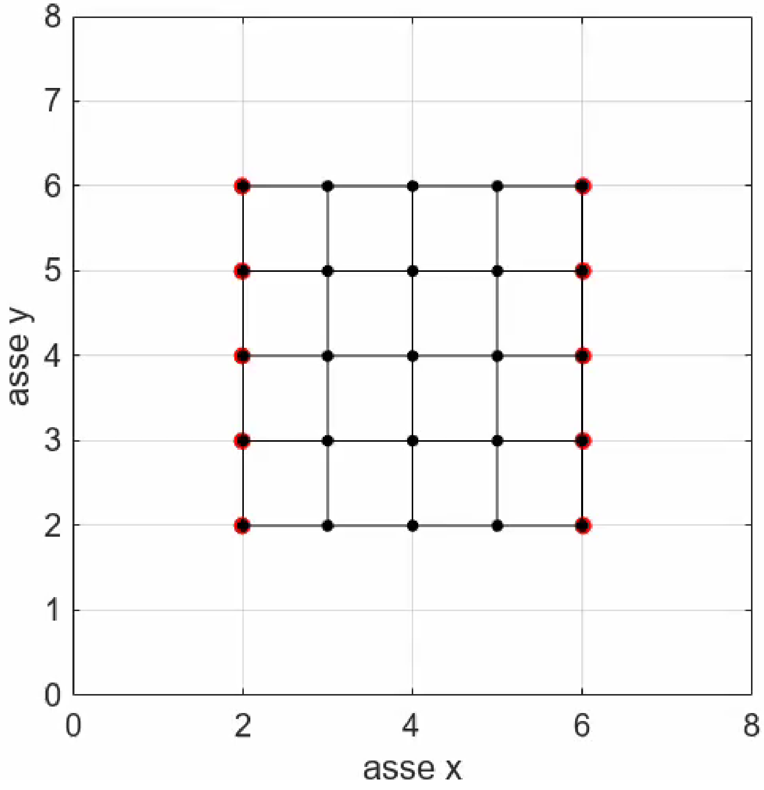
RBF mesh morphing

Through RBF mesh morphing, it is possible to modify a discretized geometry by imposing the displacement of a certain number of its nodes

Mesh Morphing driven by RBF

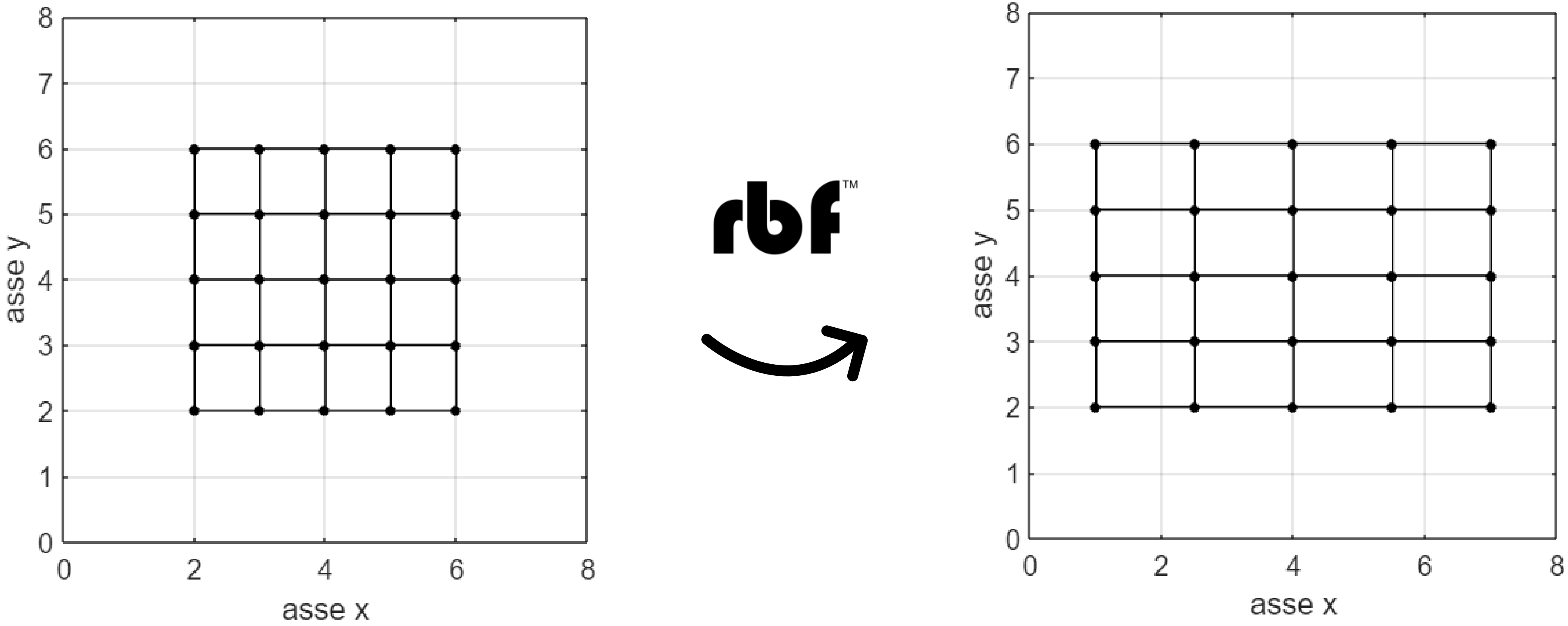
Example:





Mesh Morphing driven by RBF

Example:



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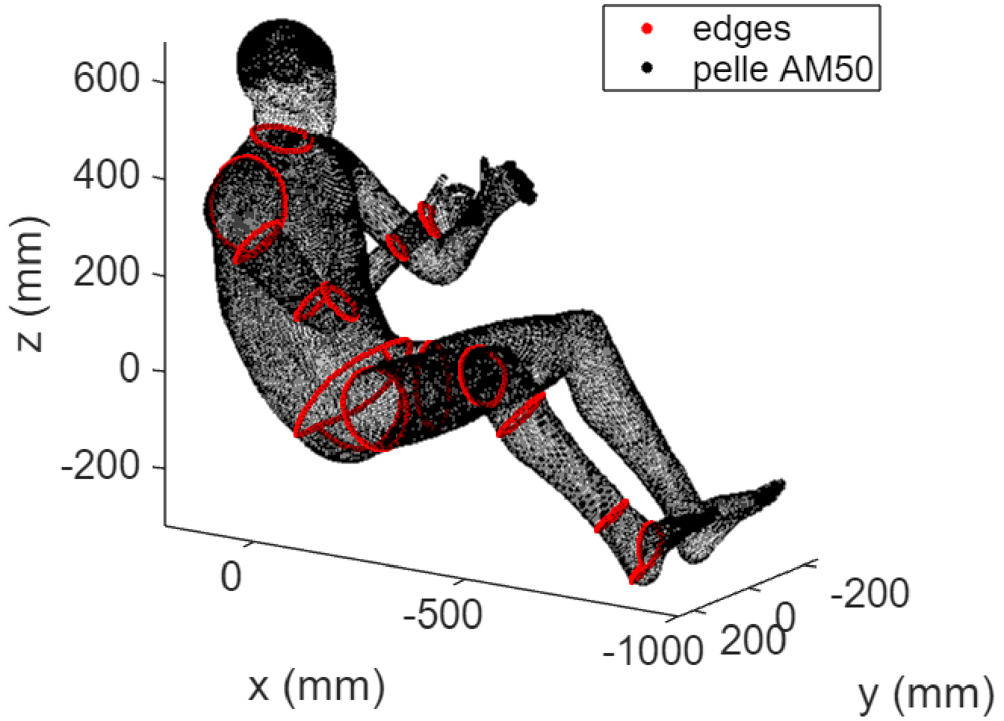
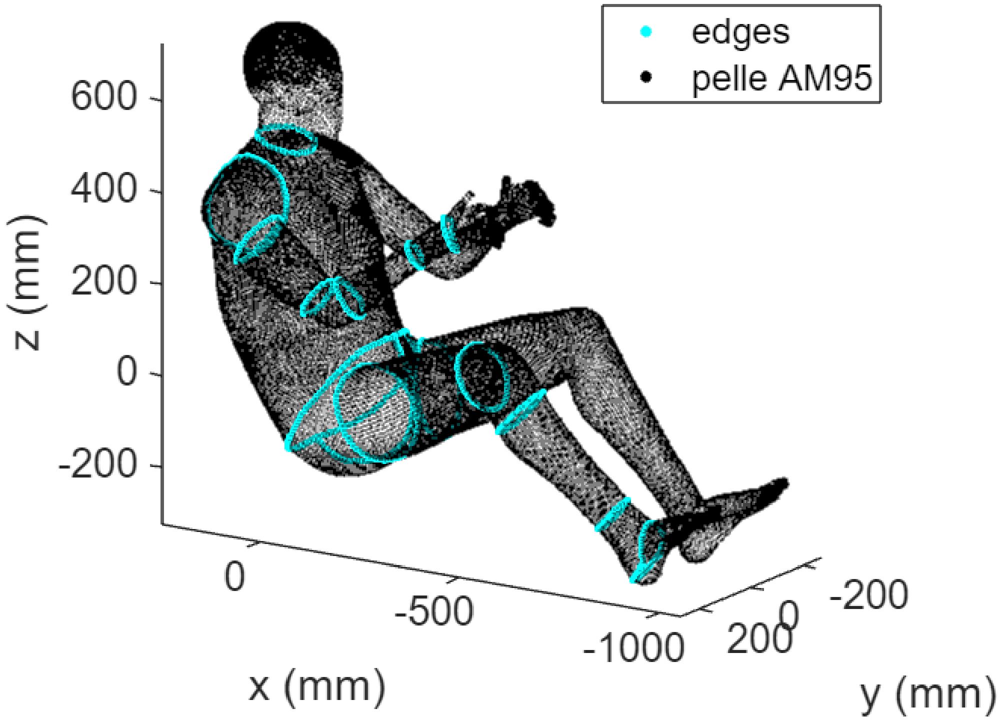
Source points selection

- Source points in AM50



- Homologous edges in AM95



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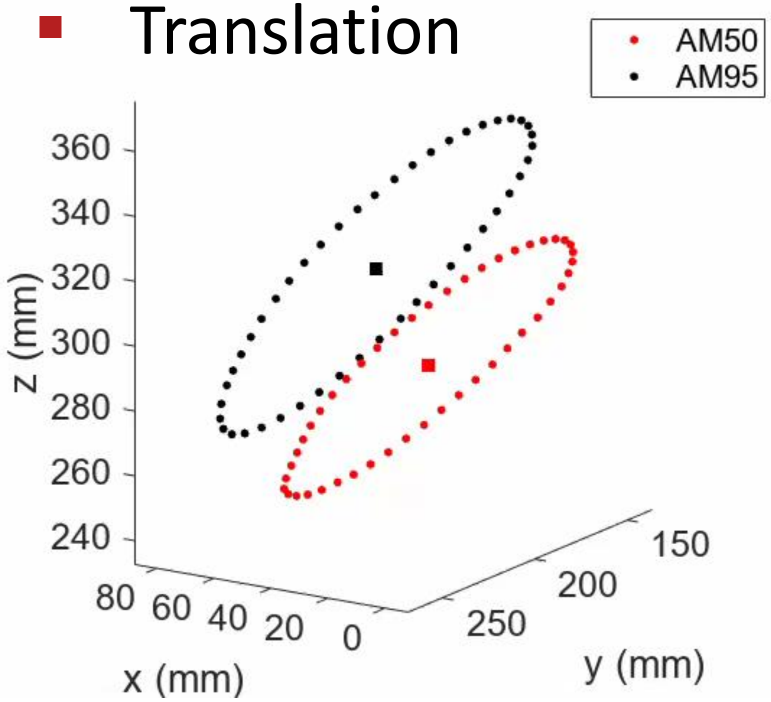
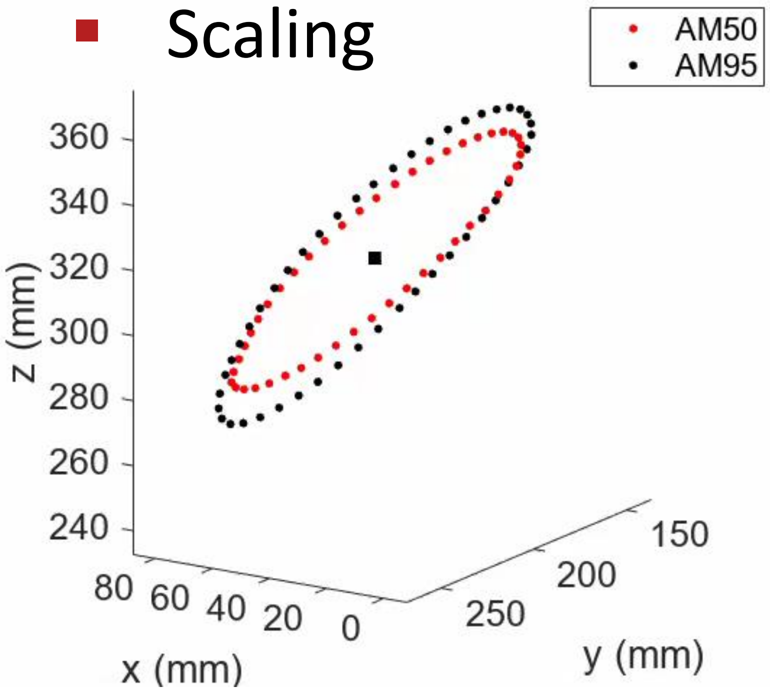
RBF displacements

- Translation



- Scaling



Combining the 2 operations ⟶ Displacements: $\boldsymbol{D_{50-95,i}}$

RBF displacements: calculation of $D_{50-95,i}$

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Being in the global reference:

$\boldsymbol{x}_{\mathbf{50},i} = \{x_{50,1}, \dots, x_{50,n}\}_i^t$ ← x-nodal coordinates of the i-th edge of AM50

$\boldsymbol{x}_{\mathbf{95},i} = \{x_{95,1}, \dots, x_{95,m}\}_i^t$ ← x-nodal coordinates of the i-th edge of AM95

and in the local barycentric reference:

$\bar{\boldsymbol{x}}_{\mathbf{50},i} = \{\bar{x}_{50,1}, \dots, \bar{x}_{50,n}\}_i^t$ ← x-nodal coordinates of the i-th edge of AM50

$\bar{\boldsymbol{x}}_{\mathbf{95},i} = \{\bar{x}_{95,1}, \dots, \bar{x}_{95,m}\}_i^t$ ← x-nodal coordinates of the i-th edge of AM95

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RBF displacements: calculation of $\boldsymbol{D}_{\mathbf{50-95},\boldsymbol{i}}$

$$\Delta_{x,i} = mean\{\boldsymbol{x}_{\mathbf{50},\boldsymbol{i}}\} - mean\{\boldsymbol{x}_{\mathbf{95},\boldsymbol{i}}\}$$

← Translation delta along x-axis

$$S_{x,i} = \frac{\max\{\bar{\boldsymbol{x}}_{\mathbf{95},\boldsymbol{i}}\} - \min\{\bar{\boldsymbol{x}}_{\mathbf{95},\boldsymbol{i}}\}}{\max\{\bar{\boldsymbol{x}}_{\mathbf{50},\boldsymbol{i}}\} - \min\{\bar{\boldsymbol{x}}_{\mathbf{50},\boldsymbol{i}}\}}$$

← Scaling factor along x-axis

$$\boldsymbol{D}_{\boldsymbol{x}\,\mathbf{50-95},\boldsymbol{i}} = \Delta_{x,i} \cdot \boldsymbol{I}_{n\times 1} + (S_{x,i} - 1) \cdot \bar{\boldsymbol{x}}_{\mathbf{50},\boldsymbol{i}}$$

likewise, working on the y and z-axys:

$$\boldsymbol{D}_{\mathbf{50-95},\boldsymbol{i}} = \begin{Bmatrix} | & | & | \\ \boldsymbol{D}_{\boldsymbol{x}\,\mathbf{50-95},\boldsymbol{i}} & \boldsymbol{D}_{\boldsymbol{y}\,\mathbf{50-95},\boldsymbol{i}} & \boldsymbol{D}_{\boldsymbol{z}\,\mathbf{50-95},\boldsymbol{i}} \\ | & | & | \end{Bmatrix}$$

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Parametric mesh morphing

- δ: modulation parameter
- $\boldsymbol{D}_{\boldsymbol{50-P,i}}$: source points displacement in the mesh morphing to the generic percentile

$$\boldsymbol{D}_{\boldsymbol{50-P,i}} = \delta * \boldsymbol{D}_{\boldsymbol{50-95,i}}$$

With δ varying linearly between 0 and 1 from the 50^{th} to the 95^{th} statistical anthropometric percentile

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Mesh morphing implementation

Automatic procedure in 4 phases:

1. Setting
2. Definition
3. Execution
4. Writing

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Setting

- Reading the LS-DYNA simulation K-FILE relative to THUMS AM50

```
..........................................................................
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*SET_NODE_LIST_TITLE
collo_50
$#       sid       da1       da2       da3       da4    solver       its         -
  89000001       0.0       0.0       0.0       0.0MECH         1
$#      nid1      nid2      nid3      nid4      nid5      nid6      nid7      nid8
  89500743  89500071  89500065  89500070  89000069  89000070  89000065  89000071
  89000743  89000044  89000883  89000742  89000885  89000888  89000741  89000890
  89000740  89000893  89000892  89000738  89000059  89000066  89000047  89000067
  89500047  89500066  89500059  89500738  89500892  89500893  89500740  89500890
  89500741  89500888  89500885  89500742  89500883  89500044         0         0
..........................................................................
................................ righe omesse ...........................
..........................................................................
```

Source points coordinates

Definition

Source points coordinates

Percentile

PTS-FILE

```
1522
-811.018 67.19753 -288.0066 -38.177466141229516 3.1974164850510567 -6.893923740617389 81000774 0 s p
-807.6782 68.16429 -292.2721 -37.94366307172289 3.2650942954424296 -7.192525414021546 81000775 0 s p
-804.5713 69.83803 -296.3405 -37.72616419255343 3.3822640773577533 -7.4773293169819155 81000776 0 s p
..............................................................................................
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109.8944 100.7405 423.7275 13.755605995039172 8.026604098779977 32.901360113398766 89589508 0 s p
150.0275 106.0441 408.1986 18.249523776210857 8.581565927666018 32.121853233288185 89589563 0 s p
27.22313 111.8411 378.0515 4.498461885936079 9.188156492952311 30.608554038536354 89589795 0 s p
```

Execution

Target points coordinates

PTS-FILE

Mesh morphing

Writing

- Writing the new simulation K-FILE

```
*NODE
 7121101        132.9127        17.49752        150.8569       0       0
 7121109       -163.0202        96.61806       -48.35065       0       0
 7121152        118.2001        21.74364         156.744       0       0
 ........................................................................
 ............................ righe omesse...............................
 ........................................................................
```

THUMS AM50

↓

```
*NODE
 7121101    150.37798102    19.41371560    166.42936123       0       0
 7121109   -171.12580417   119.26328861    -44.33608968       0       0
 7121152    133.95643805    24.15646037    173.18246829       0       0
 ........................................................................
 ............................ righe omesse...............................
 ........................................................................
```

THUMS AM50mP

Simulation

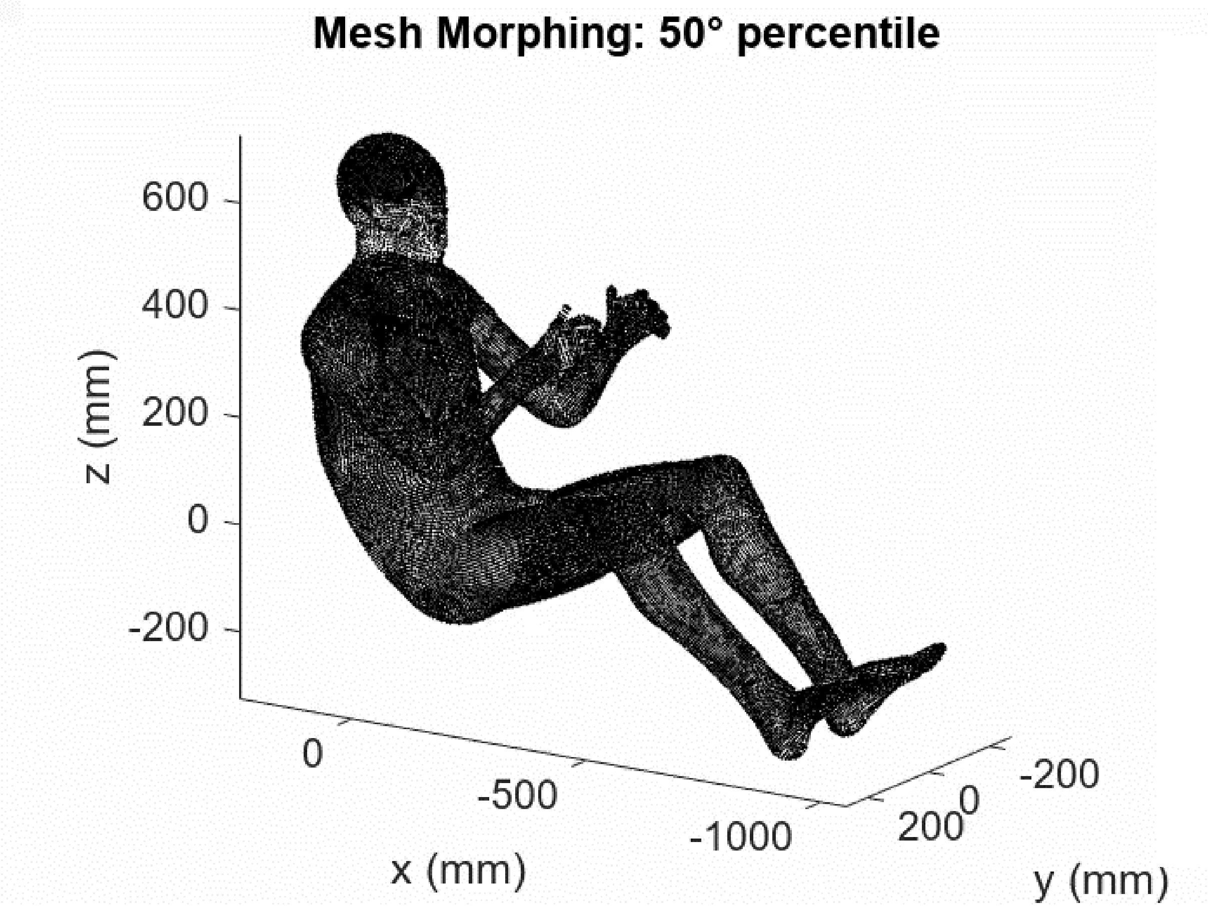
- **AM50m95:** mesh morphing to 95^{th} percentile → 100 kg
- **AM50m75:** mesh morphing to 75^{th} percentile → 89 kg
- **AM50m35:** mesh morphing to 35^{th} percentile → 65 kg

Frontal impact kinematic analysis

Simulation

Ansys / LS-DYNA

automotive CAE GRAND CHALLENGE



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Simulation

Ansys / LS-DYNA

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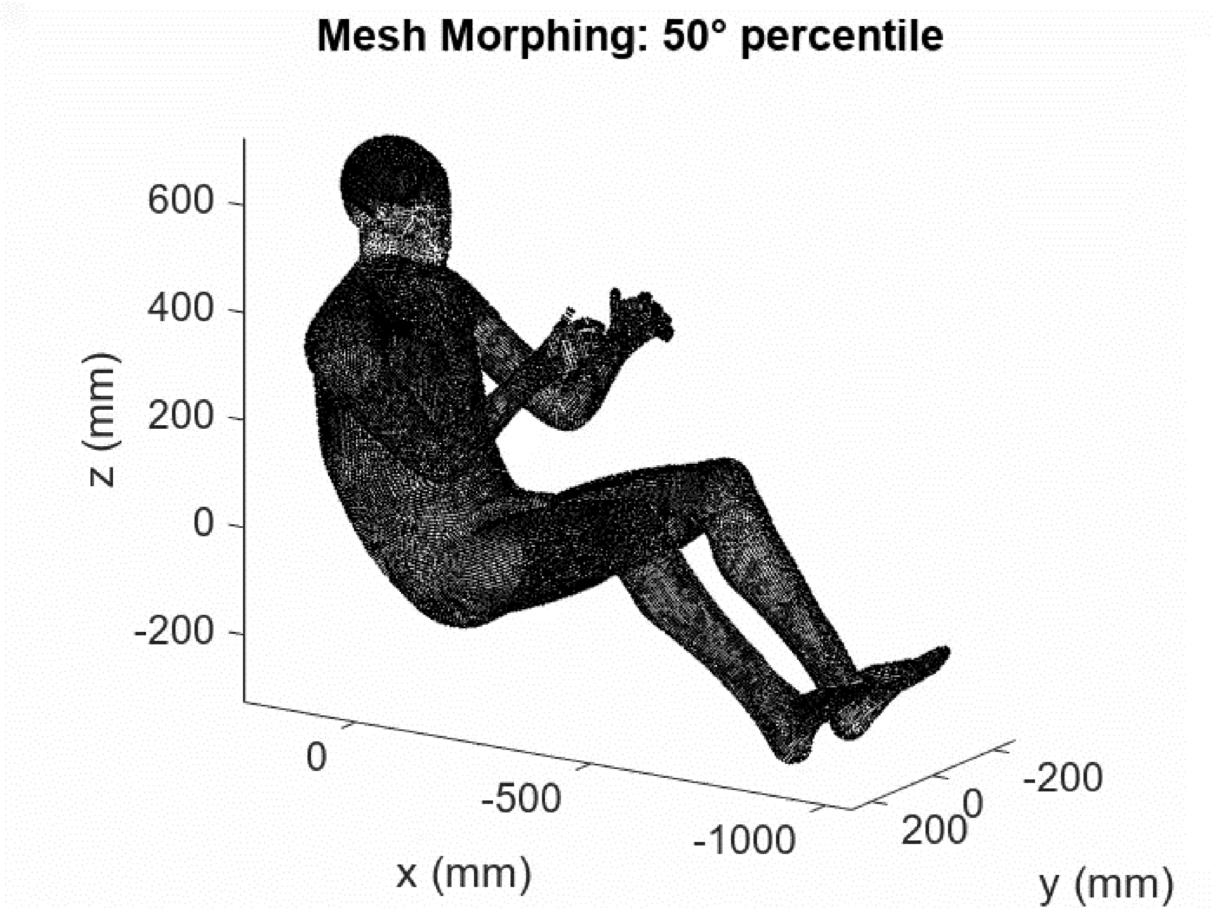

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Simulation

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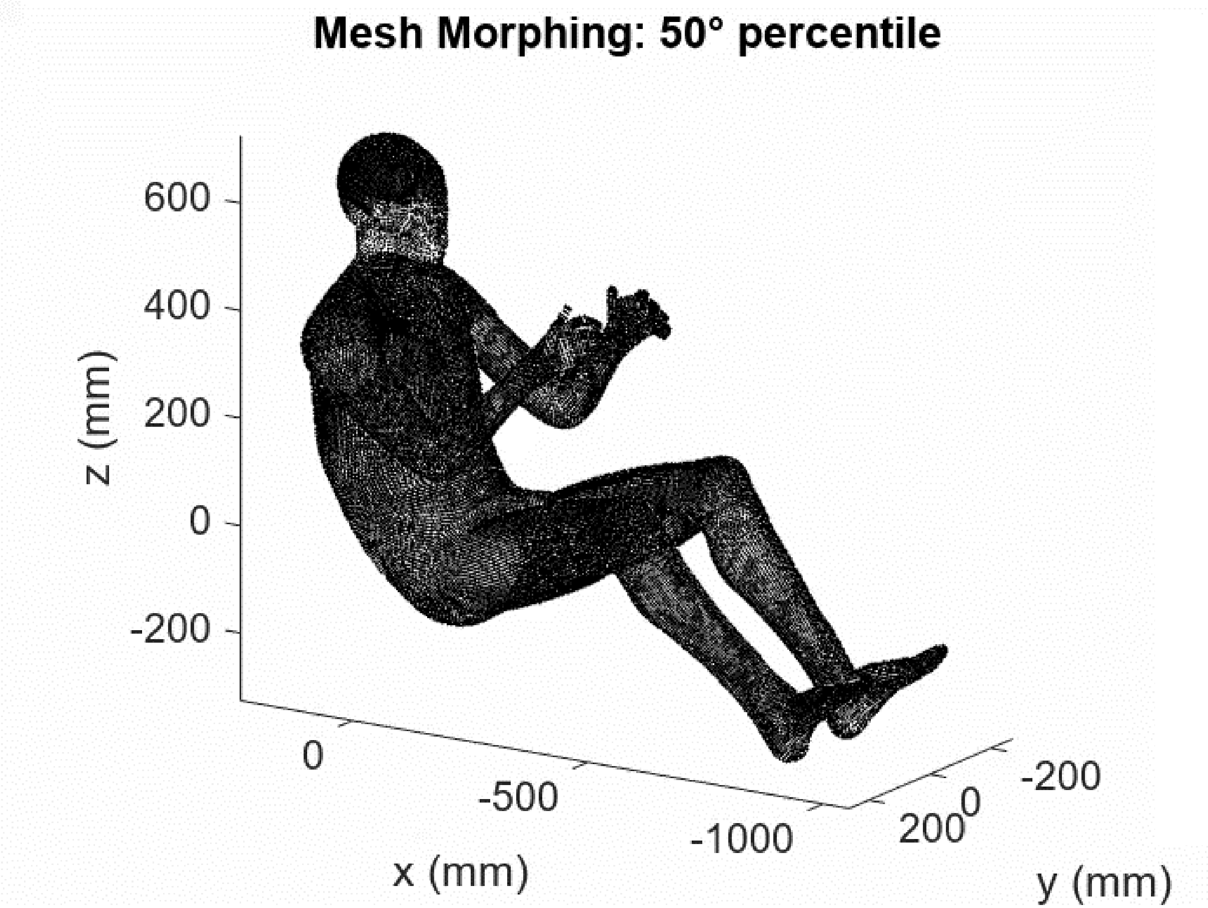

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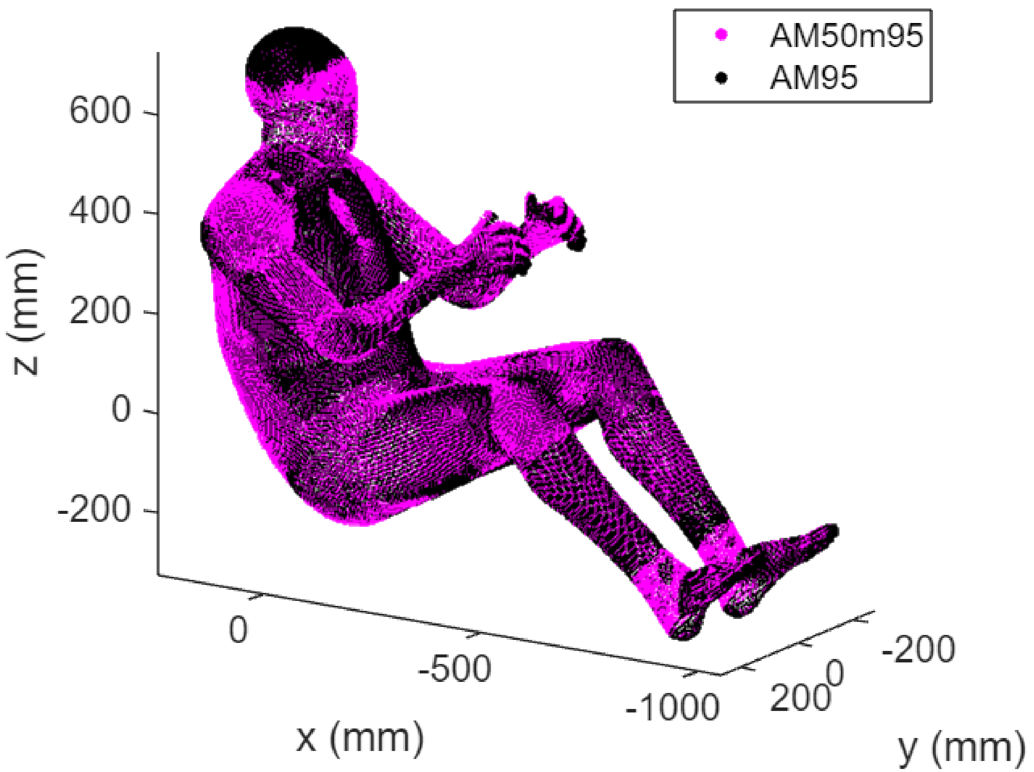
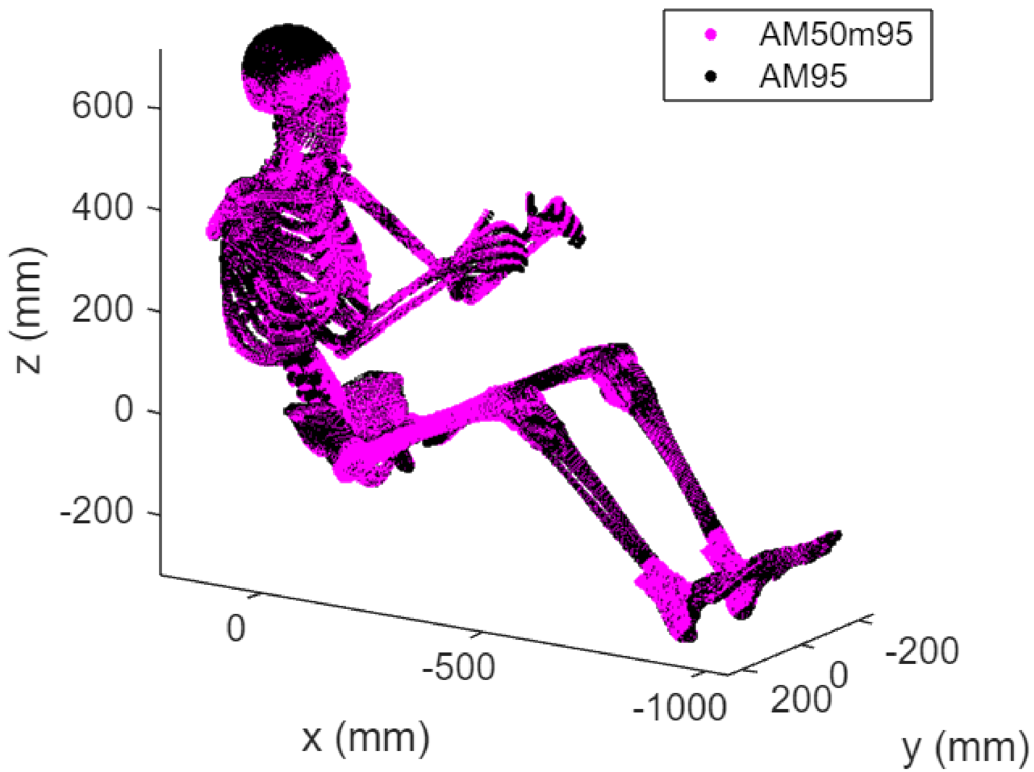
Results: graphic comparison

- Geometry quality: AM50m95 vs AM95





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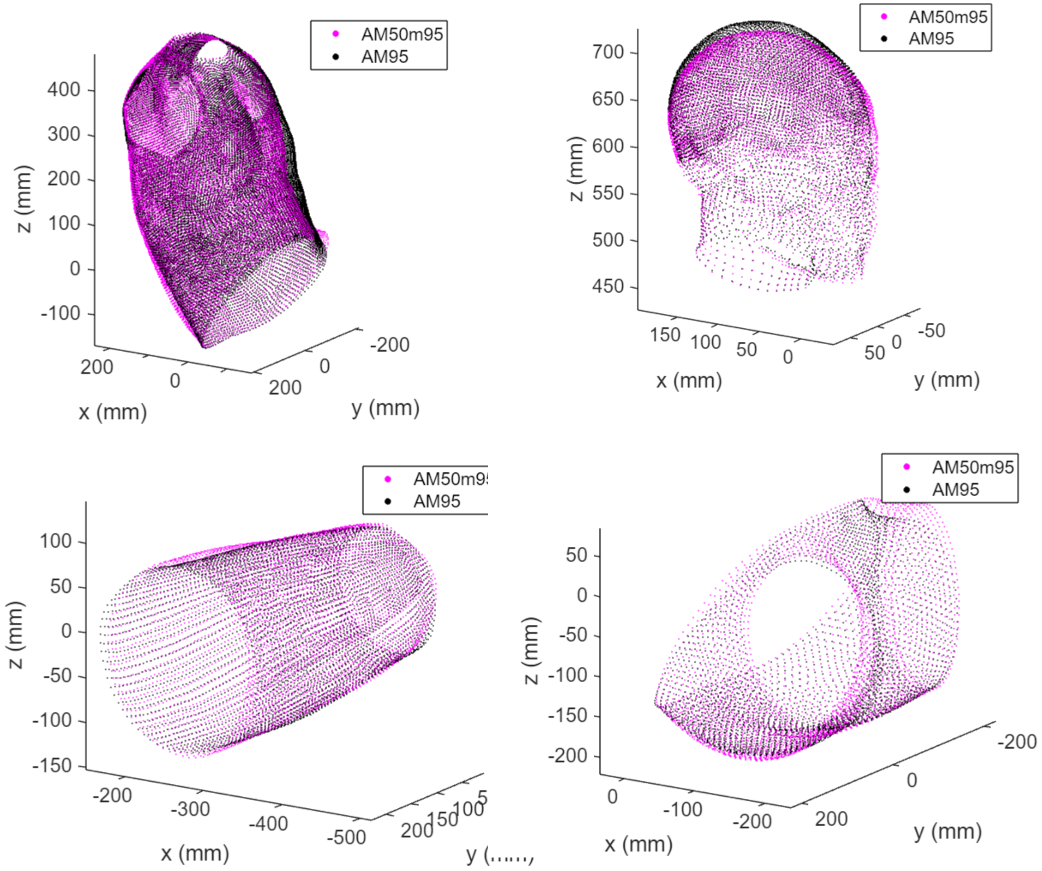
Results: MDA and MDM

- MDA: average displacement existing between homologous zones of distint meshes
- MDM: maximum displacement

Body areas comparison			
area	**MDA *[mm]***	**MDM *[mm]***	**MDA/MDM**
Busto	7.10	24.36	29%
Viso	4.05	11.45	35%
Spalla	3.42	9.06	37%
…	…	…	…
Stinco	1.68	3.14	53%
Cassa toracica	1.97	6.31	31%
Ossa pelviche	2.48	7.52	32%
Average	**3.65**	**8.46**	**34%**



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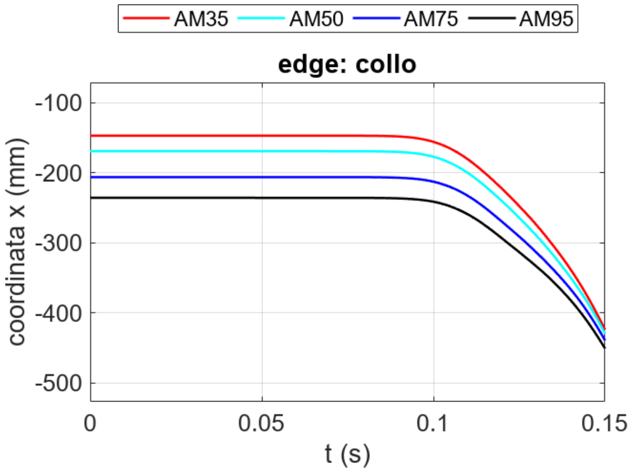
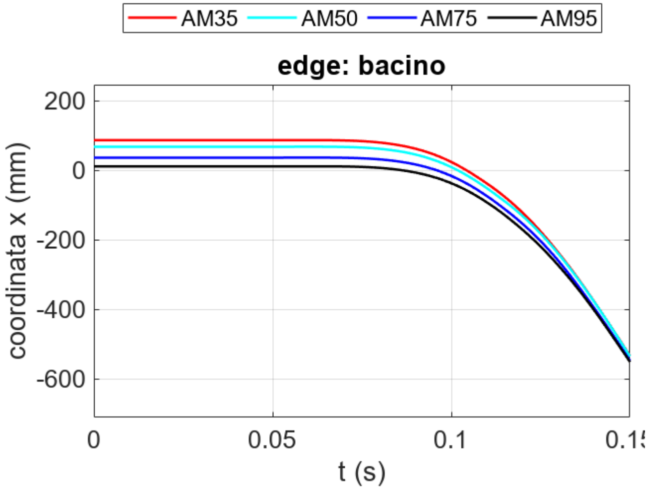
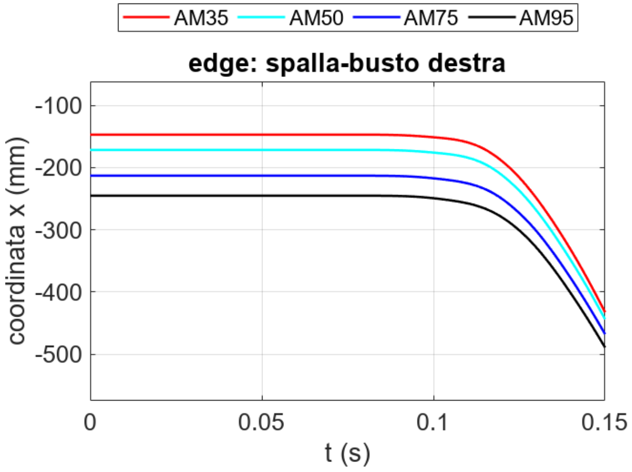
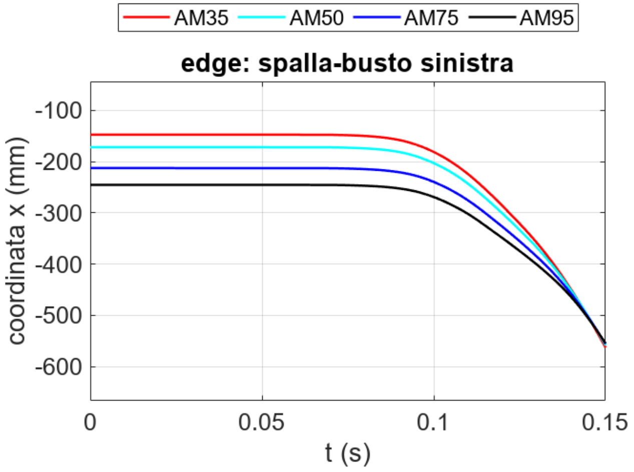
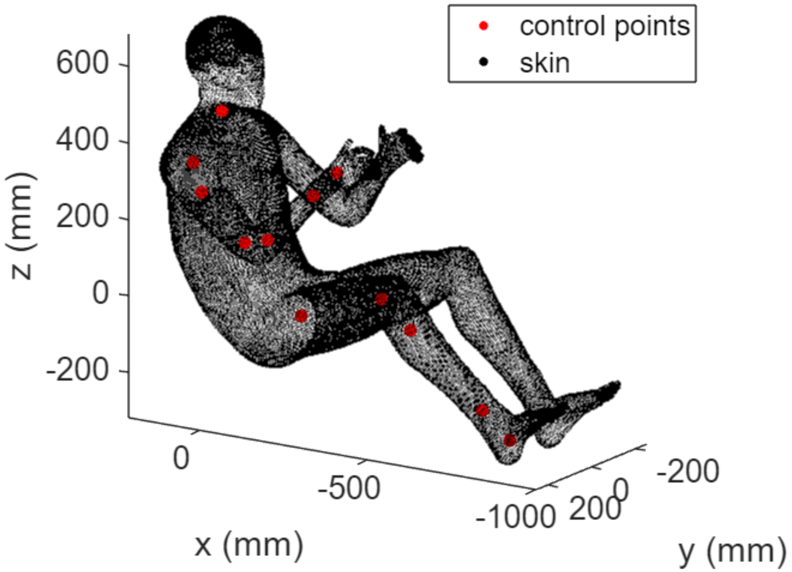
Results: kinematic analysis







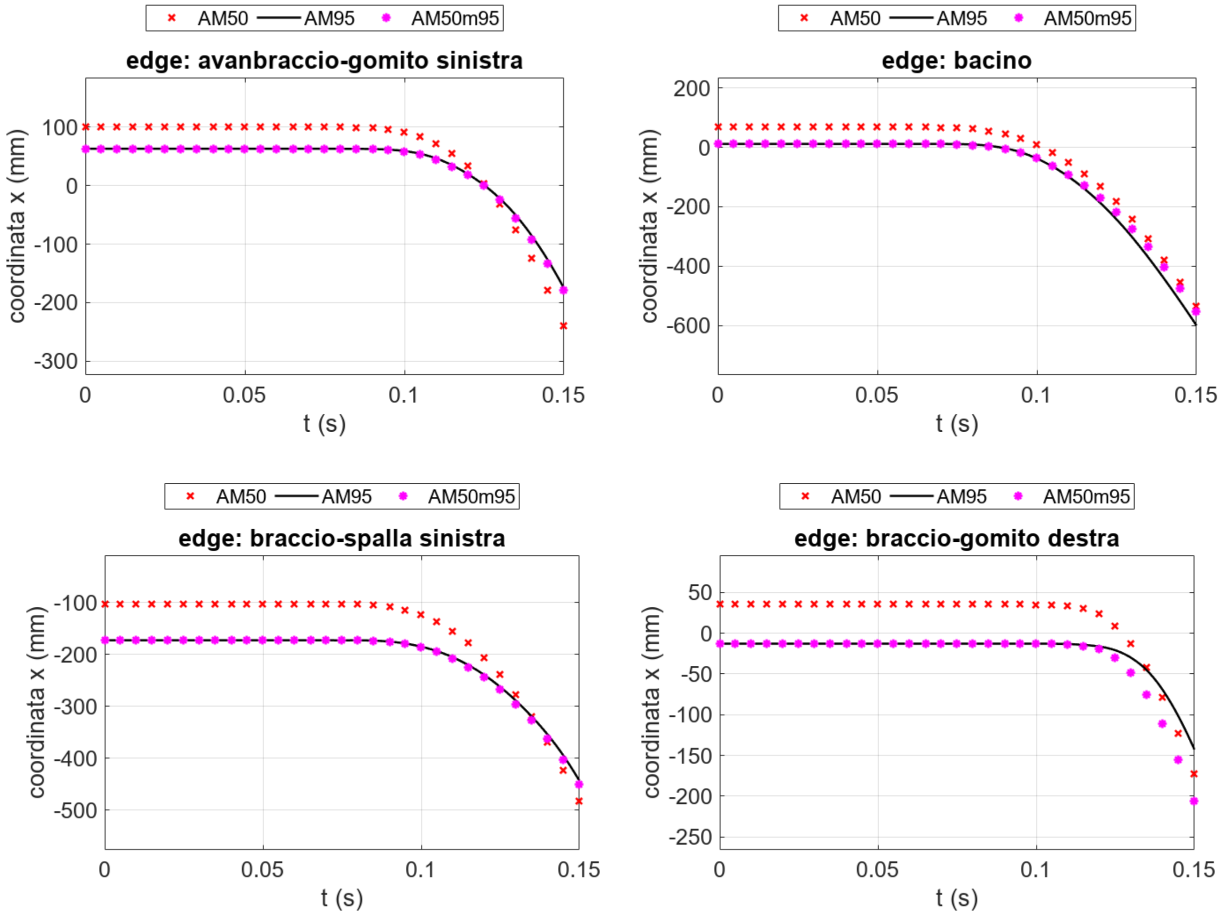




- Linear influence
- Differences introduced by the mesh morphing **0.8 mm/percentile**

Results: kinematic analysis

S_{mean} related to the AM95 *[mm]*		
Control points	***AM50***	***AM50m95***
Bacino	55.89	8.57
Collo	54.71	6.67
Busto-spalla destra	61.72	9.87
Busto-spalla sinistra	58.36	4.34
…	…	…
Stinco-caviglia destra	17.31	13.91
Stinco-caviglia sinistra	17.84	14.70
Piede destra	18.97	19.62
Piede sinistra	18.99	19.62
Average	**34.42**	**7.84**



Conclusion

METHOD

METHOD EFFICIENCY

CHOICES EFFECTIVENESS

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Thank you for your attention!

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