TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Articulation of THUMS through Reduced-Order Models

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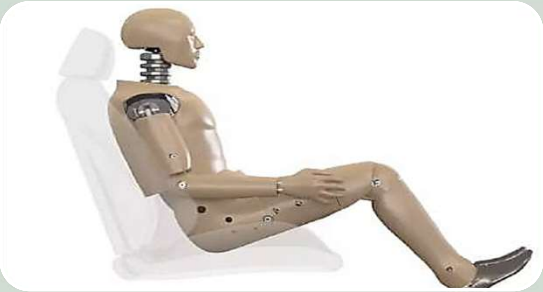
Road Safety

- **Road safety** is a primary technical objective within the engineering field..
- **Crashworthiness**: The ability of a system to protect its occupants and pedestrians during an impact.
- **Key parameters**: decelerations transmitted to the occupant; geometry of the impacting surfaces.
- **Kinetic energy variation** during the impact is absorbed by the **plastic deformation energy** of the vehicle's sheet metal.
- **Tests and simulations** are used for vehicle design (geometries and materials).



ATD (Anthropomorphic Test Device)

Dummies designed for repeatable physical measurements.

Standardized response in controlled impact conditions.

Integrated biometrics and sensor systems.

HBM (Human Body Model)

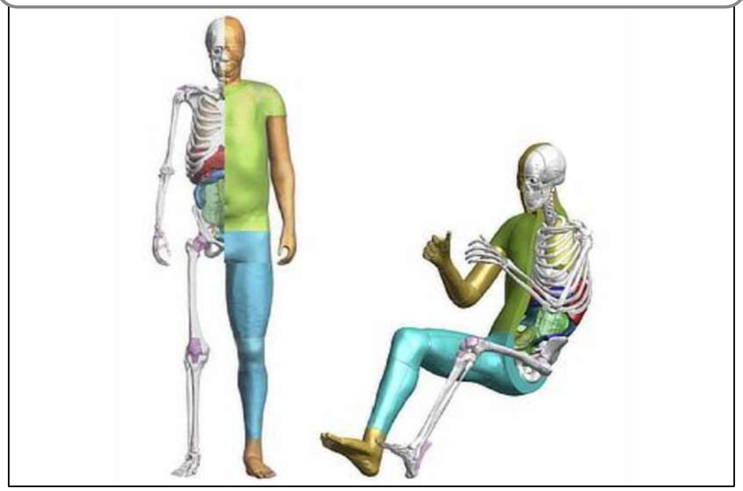
FEA simulations conducted on high-fidelity computational models.

They allow detailed analysis of internal injuries, overcoming the limitations of physical crash test dummies.

THUMS AM50 v7

- **Reference Standard:** THUMS (*Total Human Model for Safety*) is the industrial benchmark for human-impact simulation, renowned for its high biofidelic accuracy and the complexity of its models.
- **Evolution & Open Source:** Developed since 1997 by Toyota Motor Corporation and Toyota Central R&D Labs, it was released as open-source in 2019 to promote global research on safety.
- **Scientific Coordination:** The project includes the participation, as coordinator, of engineer Ernesto Mottola, graduate and PhD holder from the University of Tor Vergata.

Occupant and Pedestrian THUMS



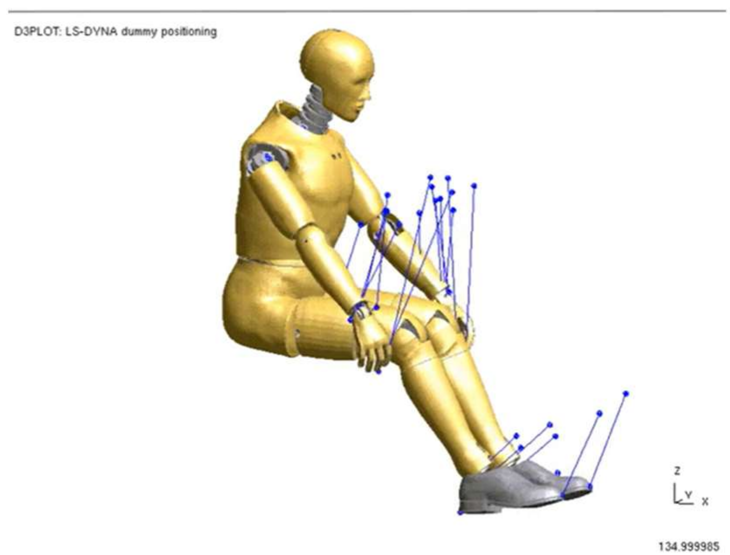
2.1M+ ELEMENTI TOTALI	**1.7M+** SOLID ELEMENTS
452K+ SHELL ELEMENTS	**12.5K** BEAM ELEMENTS

The Positioning

To simulate a real scenario, it is necessary to perform a positioning pre-simulation. For this preliminary phase, two software tools are mainly used:

- **ANSA:** mesh morphing.
- **OASYS PRIMER**: **dummy tree, cable.**

Oasys defines the positioning kinematics for the subsequent FEA simulation (high precision, computational cost, manual positioning).



From manual interactivity to automation through ROM

The approach based on tools such as Oasys Primer presents critical bottlenecks for large-scale optimization.

<u>Operational Criticalities:</u>

Extreme repetitiveness: Positioning based on standard operations but extremely demanding.

Resource expenditure: Each scenario requires a dedicated pre-simulation in LS-DYNA.

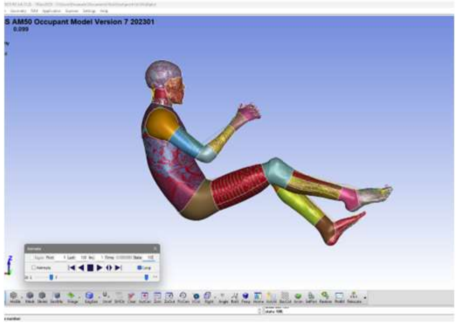
Automation via ROM

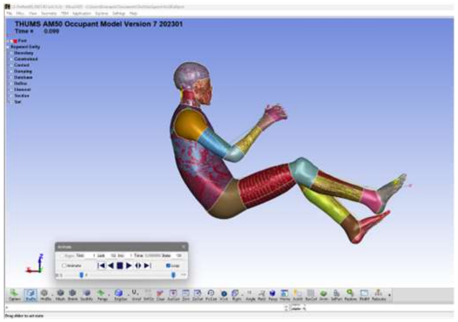
Phase	Description
Dataset	Creation of a solid data foundation through targeted simulation campaigns.
Learning	Training of a reduced model (POD) capable of learning spatial configurations.
Inference	The model provides accurate real-time results, even for previously unseen configurations.

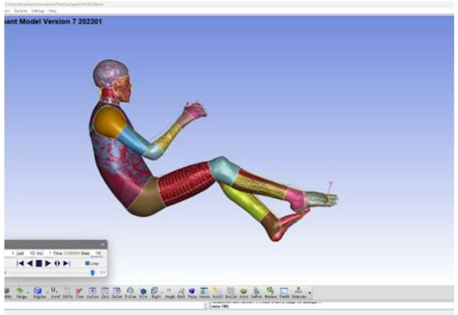
Phase 1: Dataset generation focused on the kinematic articulation of the right foot.

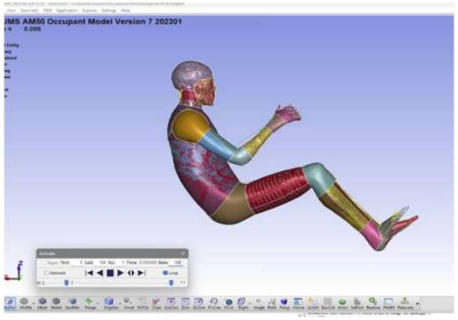
- **FEA simulations on LS-DYNA.**
- Configuration of **5 simulations managed by a cable element.**
- Fifth simulation discarded:

1. correct numerical convergence
2. non-plausible kinematics.


Case A
Reference configuration


Case B
Raised trajectory


Case C
Inward rotation


Case D
Opposite displacement

Setup : the cable

	EID	PID	N1	N2	N3	RT1	RR1	RT2	RR2	LOCAL
1	122	94300002	81007636	33	0	0	0	0	0	2

	PID	SECID	MID	EOSID	HGID	GRAV	ADPOPT	TMID
2	94300002	112	2001	0	0	0	0	0

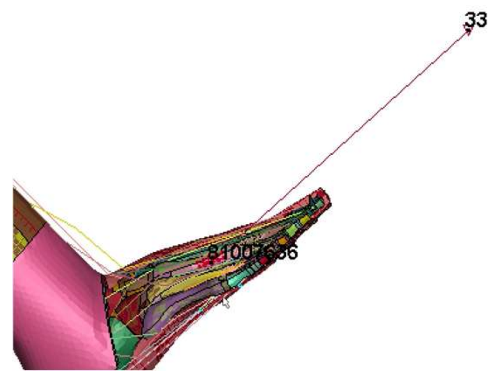
TITLE

CONSTRAINED_NODAL_RIGID_BODY

	PID	CID	NSID	PNODE	IPRT	DRFLAG	RRFLAG
1	81002101	0	92500014	81007636	0	0	0

	MID	RO	E	LCID	F0	TMAXF0	TRAMP	IREAD
1	2001	1.0000000	5000.0000	3	0.0	0.0	0.0	0

	SECID	ELFORM	SHRF	QR/IRID	CST	SCOOR	NSM	NAUPD
1	112	6	1.0000000	2	0	0.0	0.0	0



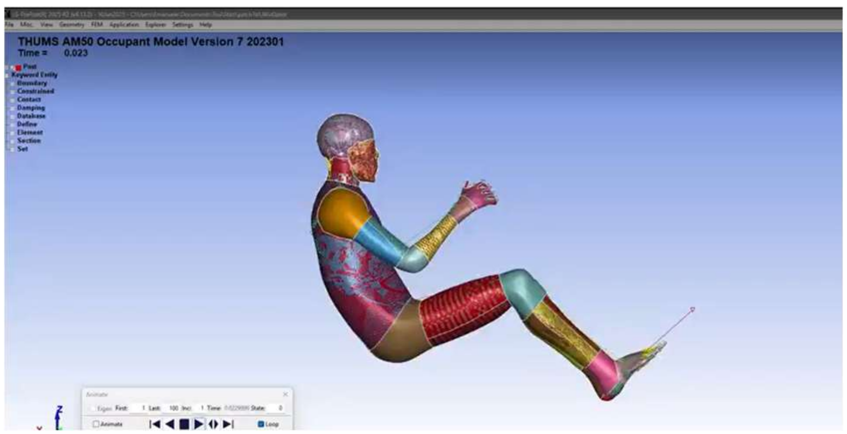
Setup : kinematics

Boundary_prescribed_motion_node

1	NID	DOF	VAD	LCID	SF	VID	DEATH	BIRTH
	81007636	1	2	145	1.0000000	0	1.000e+28	0.0

1	NID	DOF	VAD	LCID	SF	VID	DEATH	BIRTH
	81007636	3	2	146	1.0000000	0	1.000e+28	0.0

- Case A



145

2	A1	O1
	0.0	0.0

1	0.0	0.0
2	0.025	18.0
3	0.05	64.8
4	0.075	106.0
5	0.1	133.8

146

2	A1	O1
	0.0	0.0

1	0.0	0.0
2	0.025	-20.0
3	0.05	-72.0
4	0.075	-118.0
5	0.1	-148.6

Dataset Organization

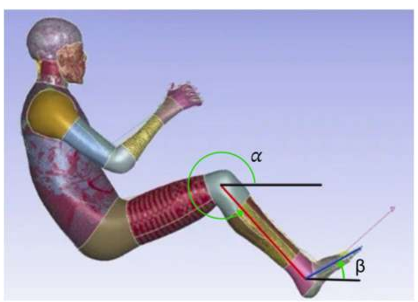
400 file d3plot

101 file vtk

(Node coordinates)

File di input

(Design Point, α, β)



DP	α (rad)	β (rad)
DP01 …..	0.316 …..	-0.234 ….

Rigid Nomenclature

D3PLOT_00	VTK_00	DP_00
D3PLOT_01A.. D3PLOT_100A	VTK_01.. VTK_25	DP_01.. DP_25
D3PLOT_01B.. D3PLOT_100B	VTK_26.. VTK_50	DP_26.. DP_50
D3PLOT_01C.. D3PLOT_100C	VTK_51.. VTK_75	DP_51.. DP_75
D3PLOT_01D.. D3PLOT_100D	VTK__76.. VTK_100	DP_76.. DP_100

Phase 2: Proper Orthogonal Decomposition

- POD allows us to rewrite a high-dimensional field $u(x, t)$ in a compact form as a linear combination:

$$S = \begin{bmatrix} \boxed{\mathbf{u}_1} & \mathbf{u}_2 & \cdots & \boxed{\mathbf{u}_m} \end{bmatrix} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,m} \\ y_{1,1} & y_{1,2} & \cdots & y_{1,m} \\ z_{1,1} & z_{1,2} & \cdots & z_{1,m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N,1} & x_{N,2} & \cdots & x_{N,m} \\ y_{N,1} & y_{N,2} & \cdots & y_{N,m} \\ z_{N,1} & z_{N,2} & \cdots & z_{N,m} \end{bmatrix}$$

Vtk_00

Vtk_100

flattening

Singular Value Decomposition

$$S = U\Sigma V^T$$

$$\mathbf{U} \in \mathbb{R}^{N\times N} \qquad \mathbf{\Sigma} \in \mathbb{R}^{N\times M} \qquad \mathbf{V} \in \mathbb{R}^{M\times M}$$

The columns correspond to the POD spatial modes ϕ_i

The column vectors represent the temporal evolution of the POD modes extracted from the snapshot matrix.

Matrix of energetic weights (diagonal).
$\sigma_1 \geq \sigma_2 \geq .. \geq \sigma_m$

Proper Orthogonal Decomposition

- The number of modes r to retain for the reconstruction of the system is based on the accumulated energy index (greater than 95%):

$$E(r) = \frac{\sum_{i=1}^{r} \sigma_i^2}{\sum_{j=1}^{K} \sigma_j^2}$$

- Reduced field representation : $S_r = U_r U_r^T S$

- Error estimation using the Frobenius norm: $\|S - S_r\|_F^2 = \sum_{i=r+1}^{K} \sigma_i^2$

- Approximation of the high-dimensional field : $u(\mathbf{x}, t) \approx \sum_{i=1}^{r} a_i(t) \phi_i(\mathbf{x})$

In the present study, the computations were performed using the rbfROM software. By setting a maximum mesh error of 5 mm, a total of 8 modes were obtained.

Phase 3 : Inference

8 Modes and their corresponding modal weights

File vtk

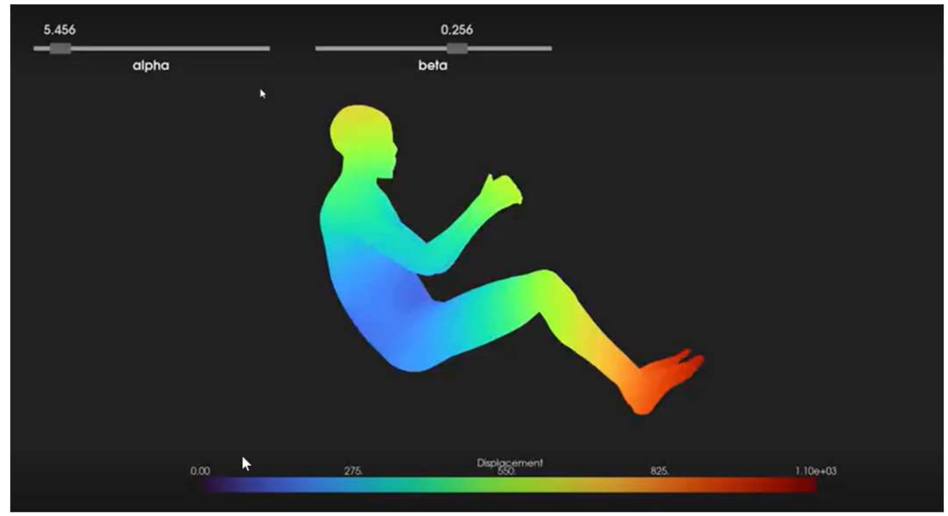
File di input

rbfROM

Interpolating function for mesh and contacts

Linear interpolation of scalar values

Predictive Model



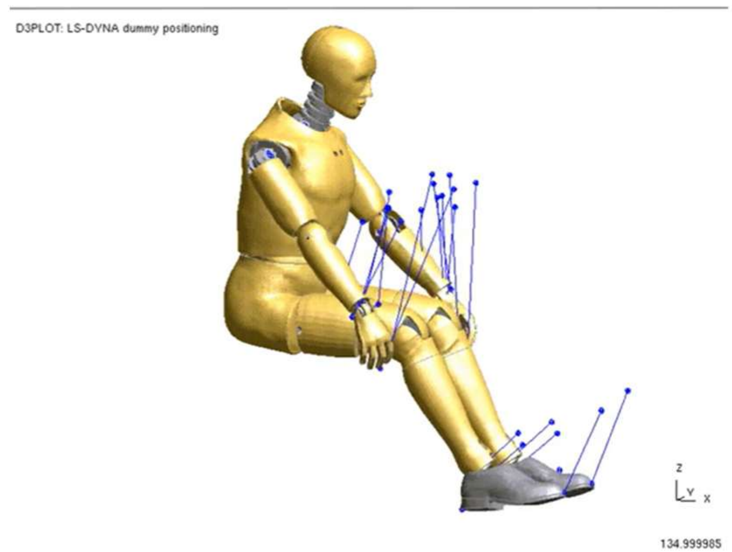
The implemented simulations extracted anatomical results; therefore, a complete space of variation was not explored α and β.
The ROM shows a high correspondence in regions close to those used for the simulations (error below 5%); in unexplored regions (especially for very small values of α and β), the correspondence tends to be lower.

Conclusions

- The methodology for building the reduced model was successfully implemented.
- A drastic reduction of the computational burden was achieved.
- High accuracy was obtained for configurations close to those explored.
- Lower accuracy was observed for configurations far from the explored domain.

Future Developments

- **Expand the experimental plan:** Execution of a DOE (Design of Experiments) using either a full-factorial method or LHS (Latin Hypercube Sampling) to achieve an exhaustive coverage of the parameter space.
- **Extend the articulation to the entire THUMS:** As a natural evolution of the work, we propose extending the system to multi-cable configurations, enabling the complex articulation of the full HBM.



Thank you for your attention

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