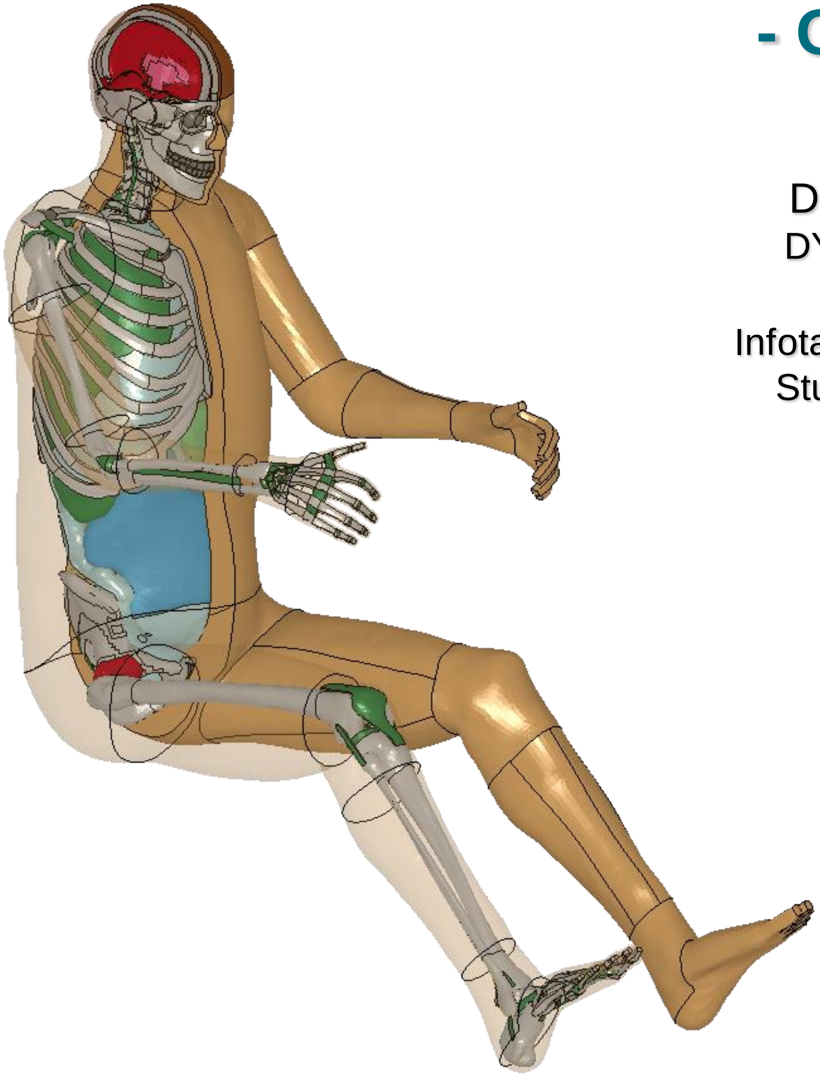
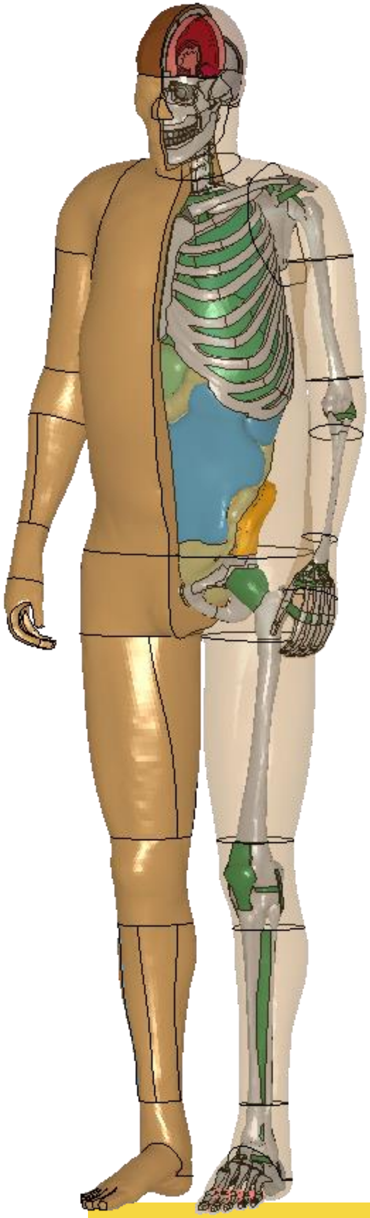


The THUMS^{TM} Human Models

- Overview -

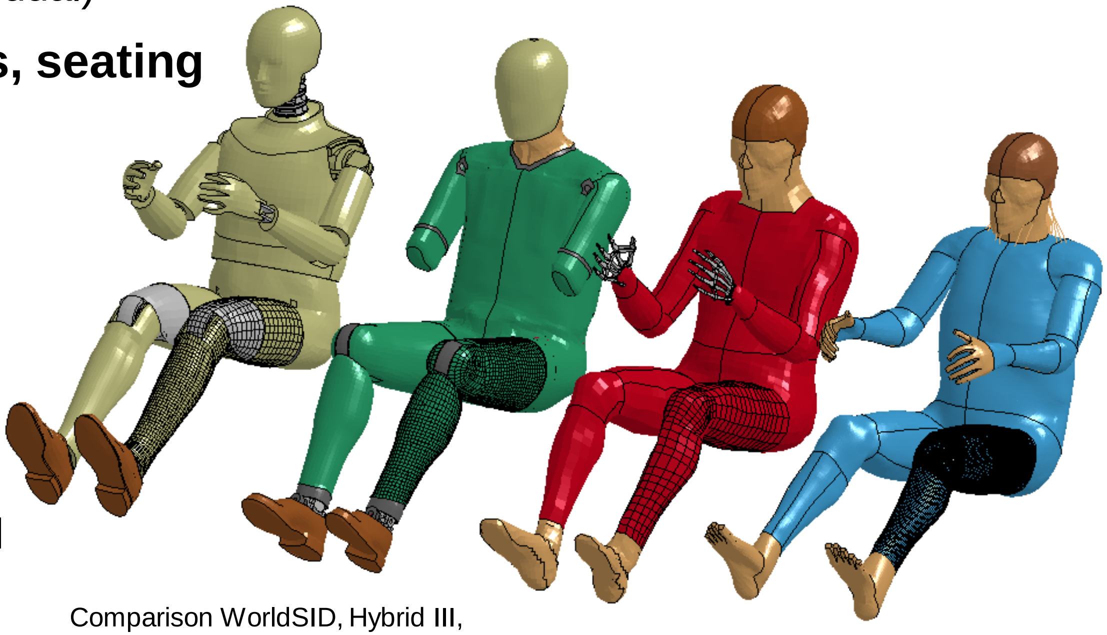
Dirk Fressmann
DYNAmore GmbH

Infotag Human Modeling
Stuttgart, Juni 2016



Human Models …

- **developed as direct model of the human body**
- **represent additional tools to evaluate injury risks and develop/improve passive and active safety systems**
  - „vehicle optimisation w.r.t. to humans, rather than dummies“
- **reproduce anatomical geometry and biomechanical properties of the human body**
  - e.g. geometry, skeletal structure, joints, stiffness- and mass distribution, etc.
  - AM50, AM95, AF05, 6YO, (individual)
- **are used in crash, ergonomics, seating comfort, sport sciences, etc.**
  - simulation of the kinematics of the human body
  - stress- and strain evaluations in bones and joints
  - recent, more detailed models may also allow deeper analysis of organ injuries or more general injury mechanisms

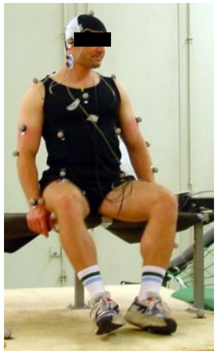


Comparison WorldSID, Hybrid III, THUMS V3, THUMS V4

From Dummy to Human Model

- From human to dummy and to virtual dummy model
- From human to virtual (numerical) human model

Experiment

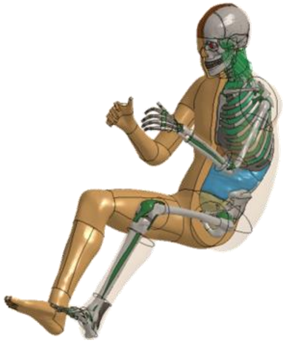


human

Model

Numerical Simulation

numerical human model



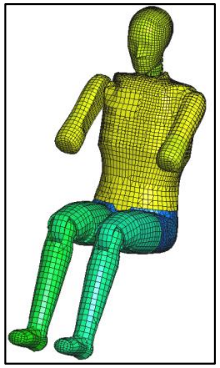
Model

permanent development

Crash Test Dummy

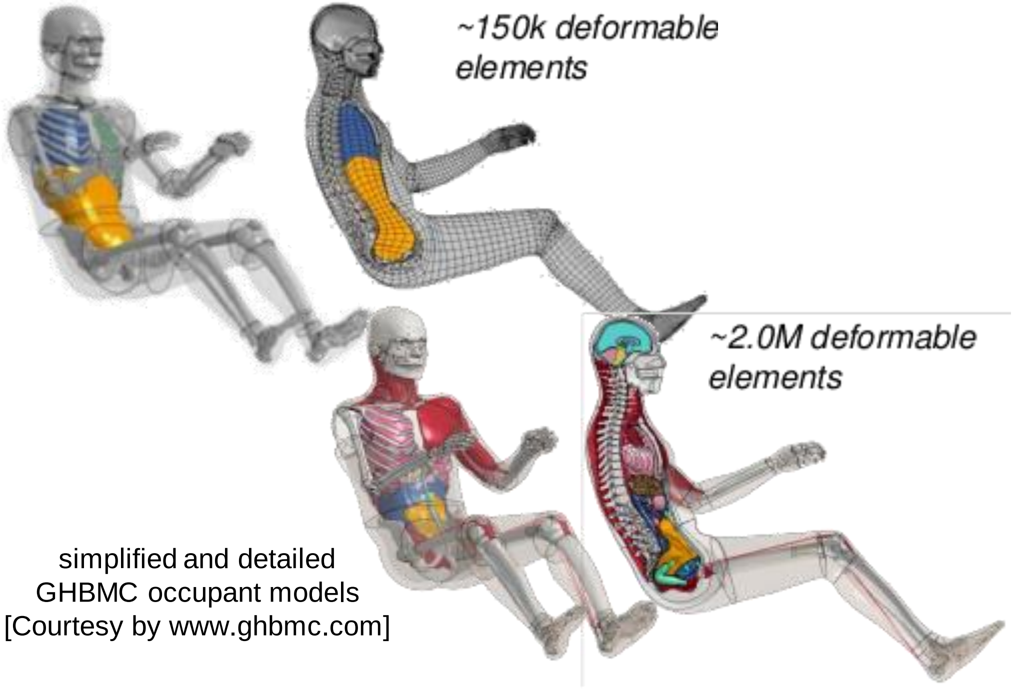
Model

numerical dummy-model

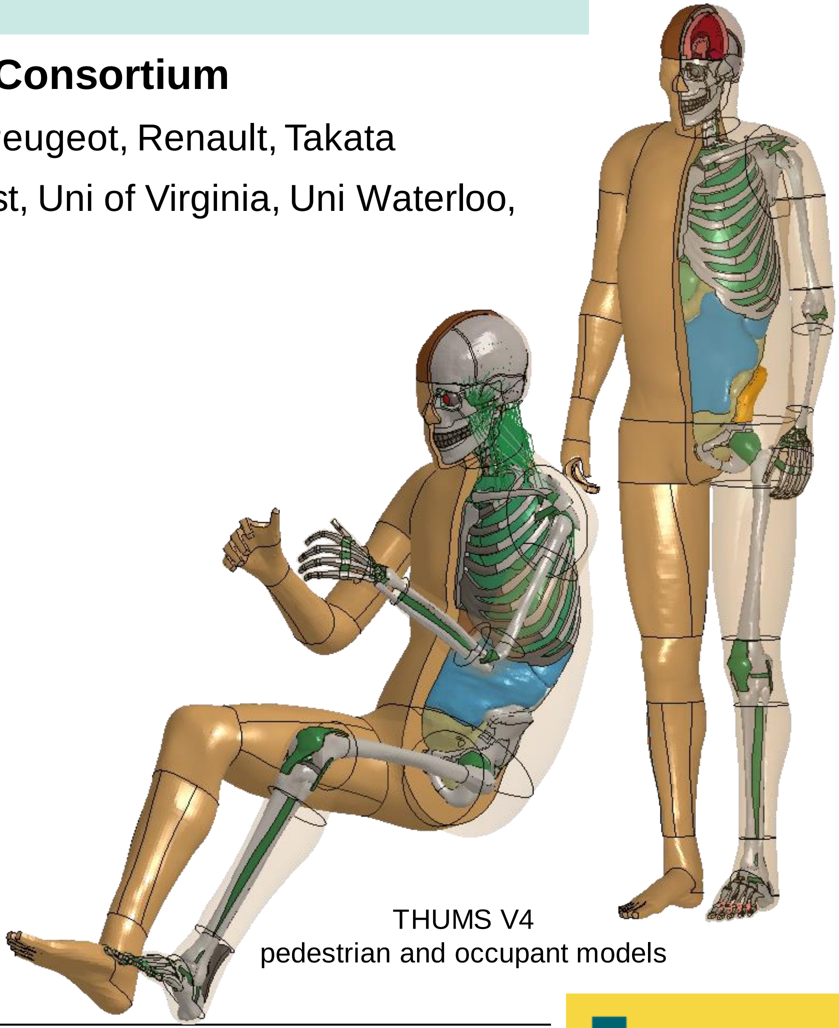


Available Human Models

- **THUMS™ – Total HUman Model for Safety**
  - developed by *Toyota Motor Corporation* and *Toyota Central R&D Labs.* Inc. since 2000
  - additional research institutes involved (e.g. WSU, Detroit/Michigan)
  - 2 versions with 2 levels of detailing
- **GHBMC-Models – Global Human Body Model Consortium**
  - Members: Chrysler, GM, Honda, Hyundai, Nissan, Peugeot, Renault, Takata
  - development at various US universities (Wake Forest, Uni of Virginia, Uni Waterloo, IFSTTAR)



simplified and detailed GHBMC occupant models [Courtesy by www.ghbmc.com]



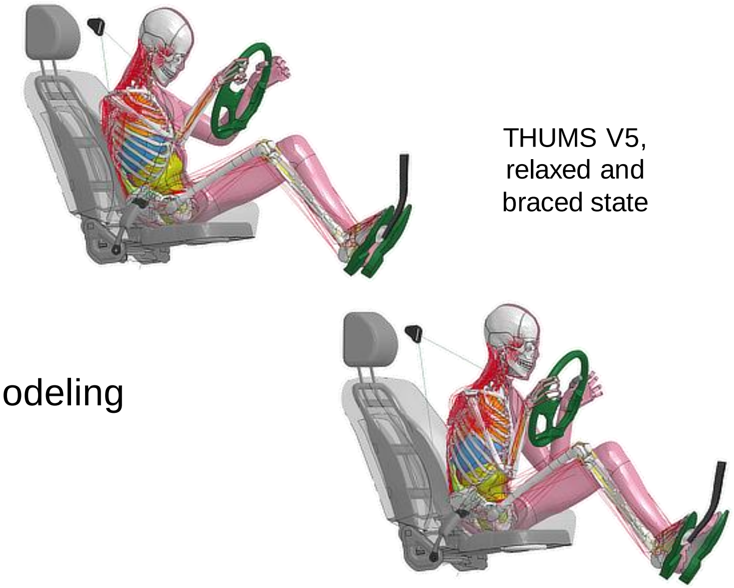
THUMS V4
pedestrian and occupant models

Model Variants and Versions

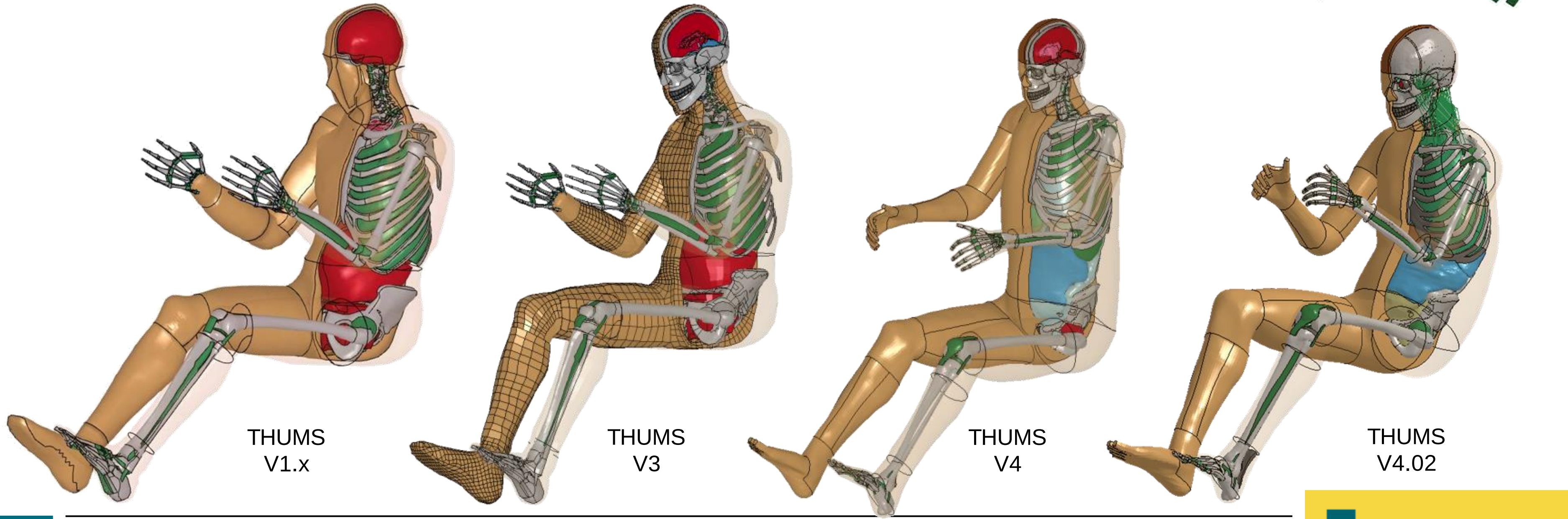
- **Versions**

  not available anymore

  - ~~1.0 – first version (since ~2000)~~
  - ~~1.4/1.6 – first usable generation (since 2004)~~
  - ~~3.0 – third generation (beginning of 2008)~~
  - 4.0x – fourth (current) generation (end 2010)
    current version: Version 4.02
  - Version 5.0 – based on Version 3, including muscle modeling
- **academic and commercial versions available**
- **only civil usage permitted**



THUMS V5, relaxed and braced state



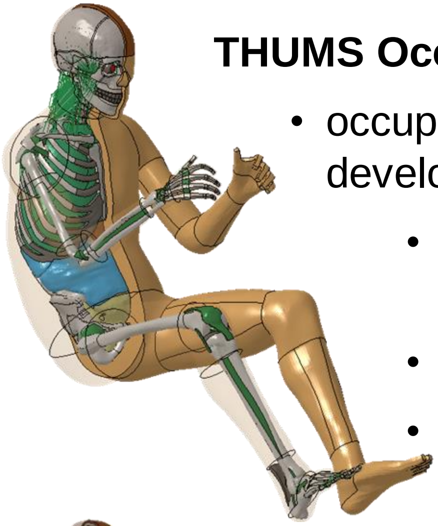
THUMS V1.x

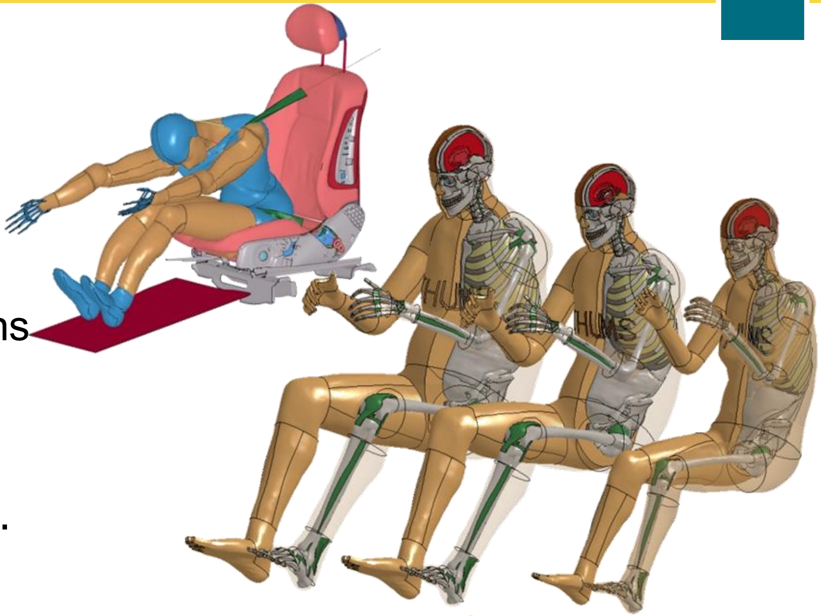
THUMS V3

THUMS V4

THUMS V4.02

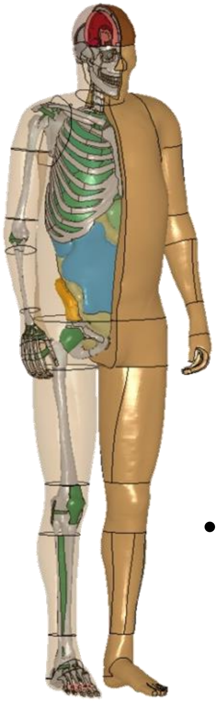
Model Variants and Versions

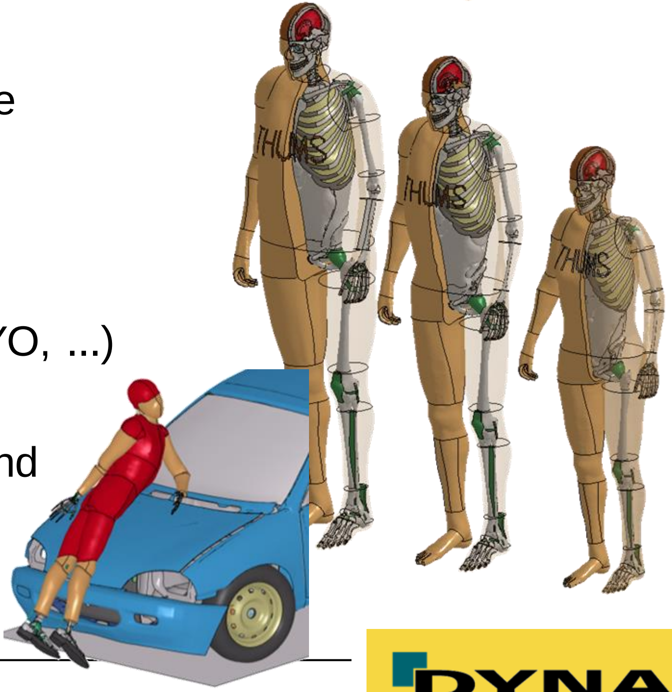




THUMS Occupant Model

- occupant simulations, belt development, airbags, etc.
  - higher biofidelity
    → front/side/rear crash situations
  - driver & co-driver postures
  - interest in “THUMS Family”
    AM95, AM50, AF05, etc.





THUMS Pedestrian Model

- pedestrian safety simulations (head impact time and location, qualitative injury evaluation)
- variation of posture, stance or model size
- additional interest in „THUMS Family“
  (different model sizes – AM95, AM50, AF05, 6YO, ...)

- basically same modelling techniques for occupant and pedestrian with slight modifications
  (V3: internal organs, shoulder, material properties + failure behaviour)

Model Variants and Versions

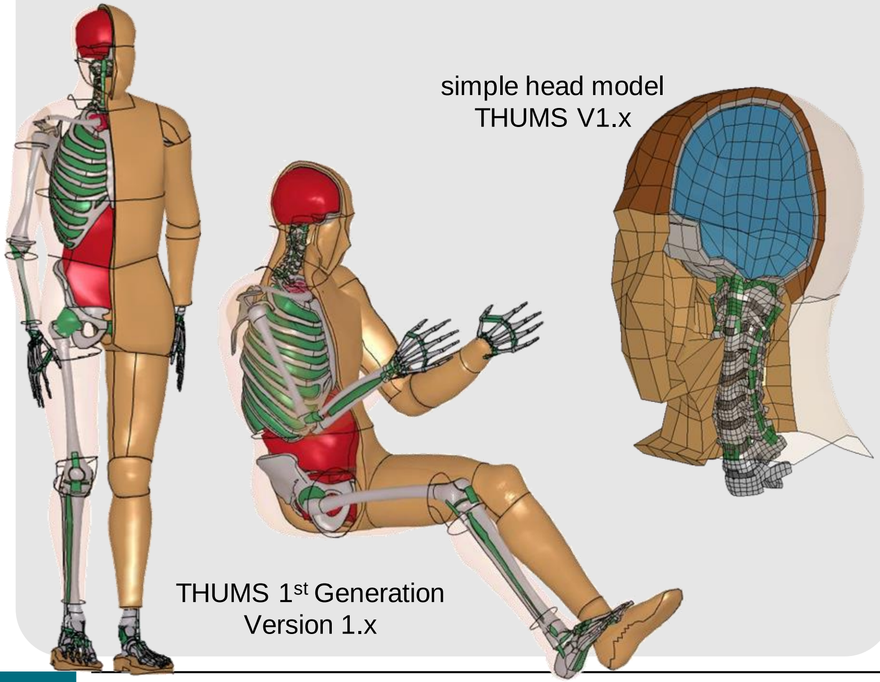
THUMS Model Versions 1.x and 3.0

- mostly based on literature data (geometry and material properties)
- simple materials (mostly elastic, elastic-plastic, viscoelastic)
- AM50 model size, comparable to size of corresponding dummy models
- exclusively used for kinematical evaluations

!!! not available anymore !!!

Versions 1.4/1.6 (ca. 2004-06)

- kinematical model (skeletal structure, joints, flesh, simplified organs, simple head model)

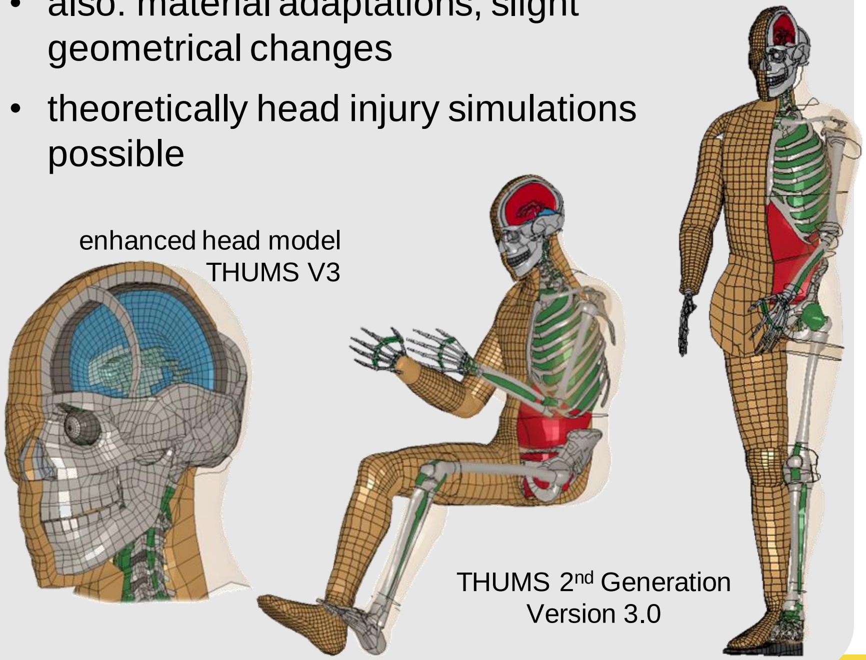


simple head model
THUMS V1.x

THUMS 1st Generation
Version 1.x

Version 3.0 (beginning of 2008)

- refined head model (based on CT-scans)
- also: material adaptations, slight geometrical changes
- theoretically head injury simulations possible



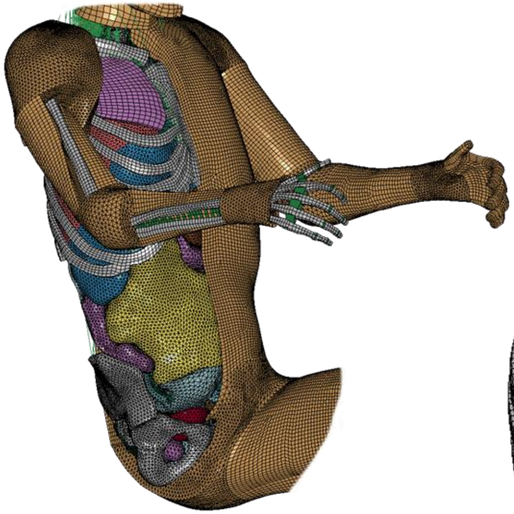
enhanced head model
THUMS V3

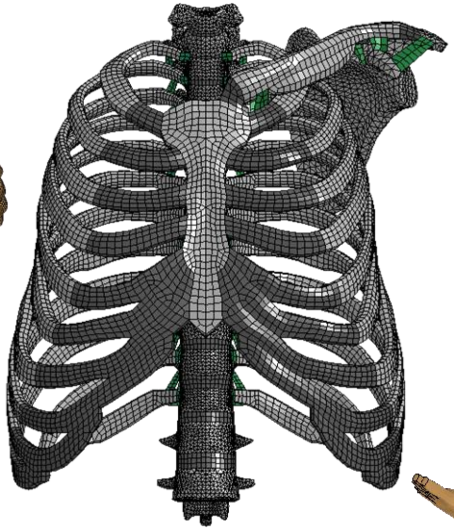
THUMS 2nd Generation
Version 3.0

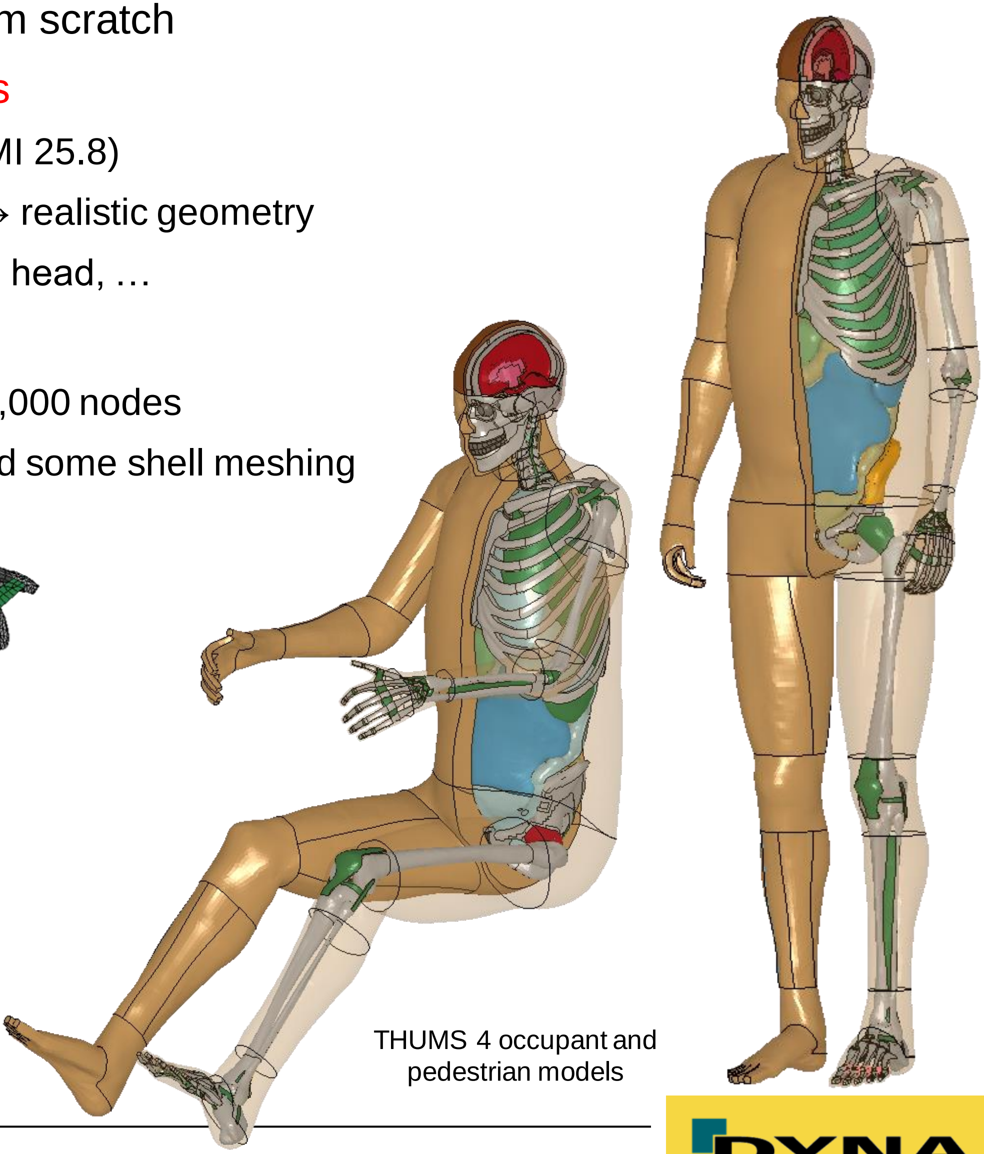
Model Variants and Versions

Current Version: THUMS Model Version 4.x

- no model update → new model rebuilt from scratch
- geometry obtained from medical CT scans
  - basis: 39 year-old male (173cm, 77.3kg, BMI 25.8)
  - scaled to AM50 model (178.6cm, 74.3kg) → realistic geometry
  - very high detailing of joints, internal organs, head, …
- model parameters
  - element size 3-5mm, 1.8Mio elements, 630,000 nodes
  - mainly solid elements (hexa/tetra mesh) and some shell meshing

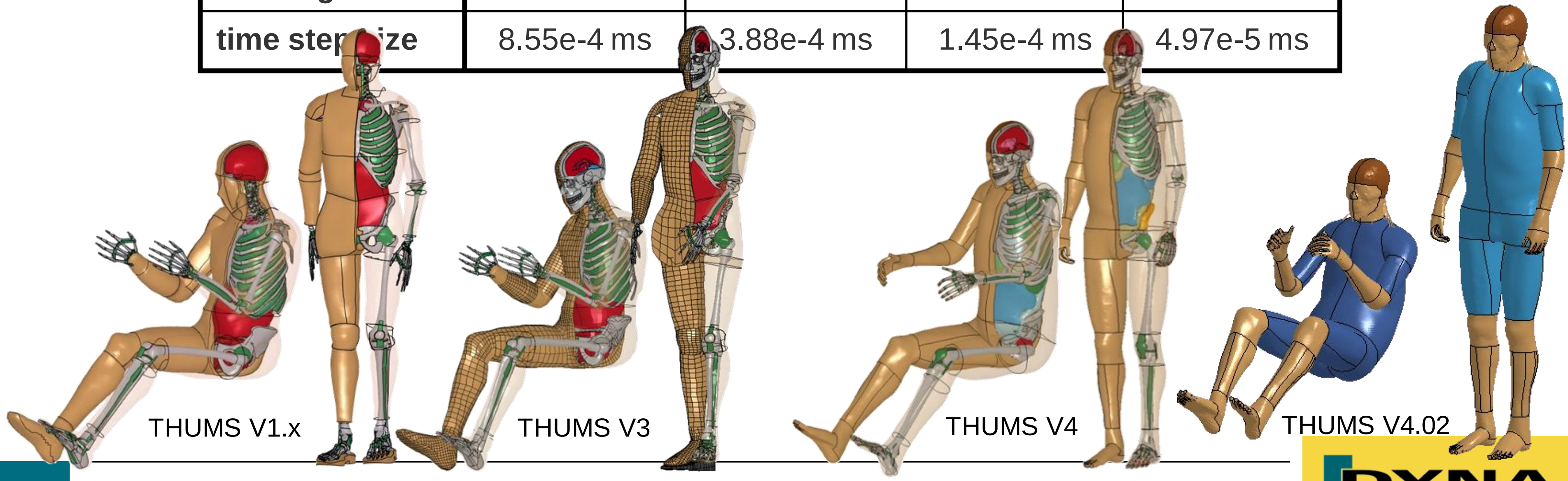

occupant upper body


pedestrian thorax


THUMS 4 occupant and pedestrian models

Model Variants and Versions

THUMS *occupant models*	**THUMS V1.61** (not available)	**THUMS V3.0** (not available)	**THUMS V4.0**	**THUMS V4.02** (current)
parts	1,350	1,576	1,273	1,293
nodes	66,729	104,489	628,358	762,997
elements	91,204	143,044	1,755,284	1,921,772
- deformable	70,019	118,484	1,749,575	1,916,310
- **rigid**	21,185	24,560	5,709	5,462
contacts	176	220	19	9
- tied	21	30	9	0
- **sliding**	155	190	10	9
time step size	8.55e-4 ms	3.88e-4 ms	1.45e-4 ms	4.97e-5 ms

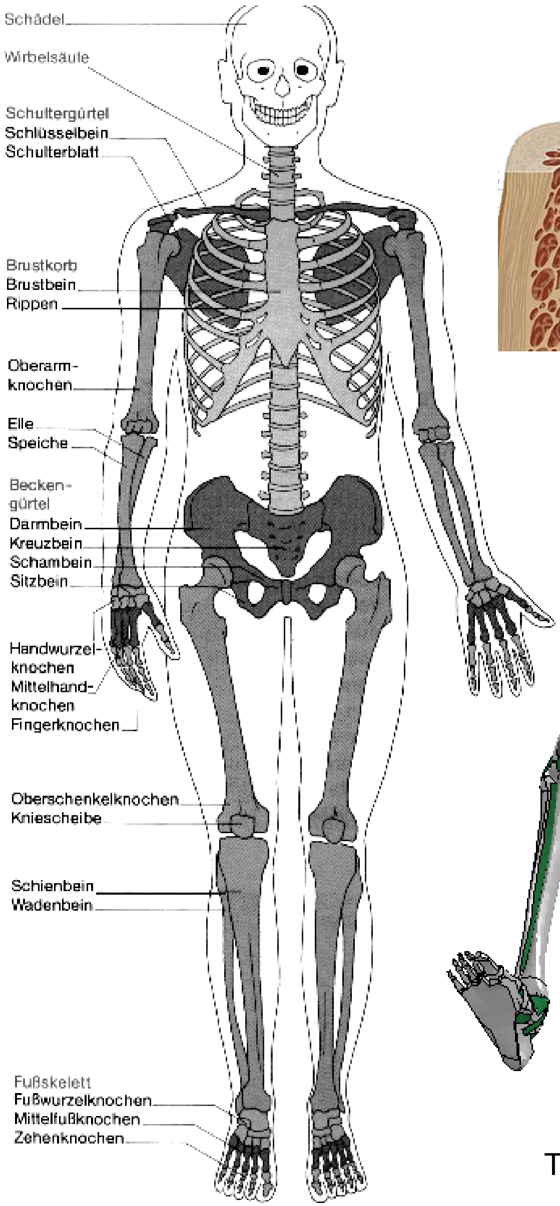


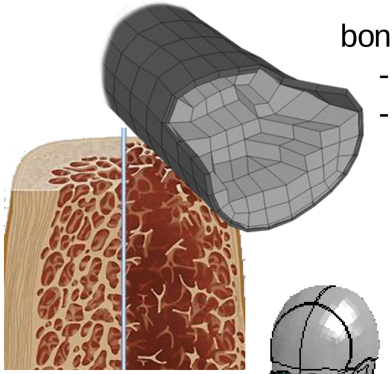
THUMS Validation Basis

- **Geometry (V1/3) and materials mainly from literature**
  - Yamada H., *Strength of Biological Materials*, Williams & Wilkins Company, 1970
  - Clemente, C.D., *Gray‘s Anatomy, 30th American Edition of the Anatomy of the Human body* by Henry Gray, Lea & Febiger, PA, 1985
  - Schneider, L.W. et al., *Development of anthropometrically-based design specifications for an advanced adult anthropomorphic dummy family*, Volume 1, UMTRI-83-53-1, NHTSA, 1983
  - and others.
  - **Experiments on human material ethically highly problematical**
- **Standard-Pendulum tests validated by Cadaver Tests (Ethics?)**
  - Thorax – lateral, frontal; Pelvis – lateral
  - Leg – lateral knee impact
  - Head/neck – lateral and frontal impact
  - Evaluation of ***test corridors***, thus upper and lower bounds of experimental data, mainly in the form of force-intrusion curves

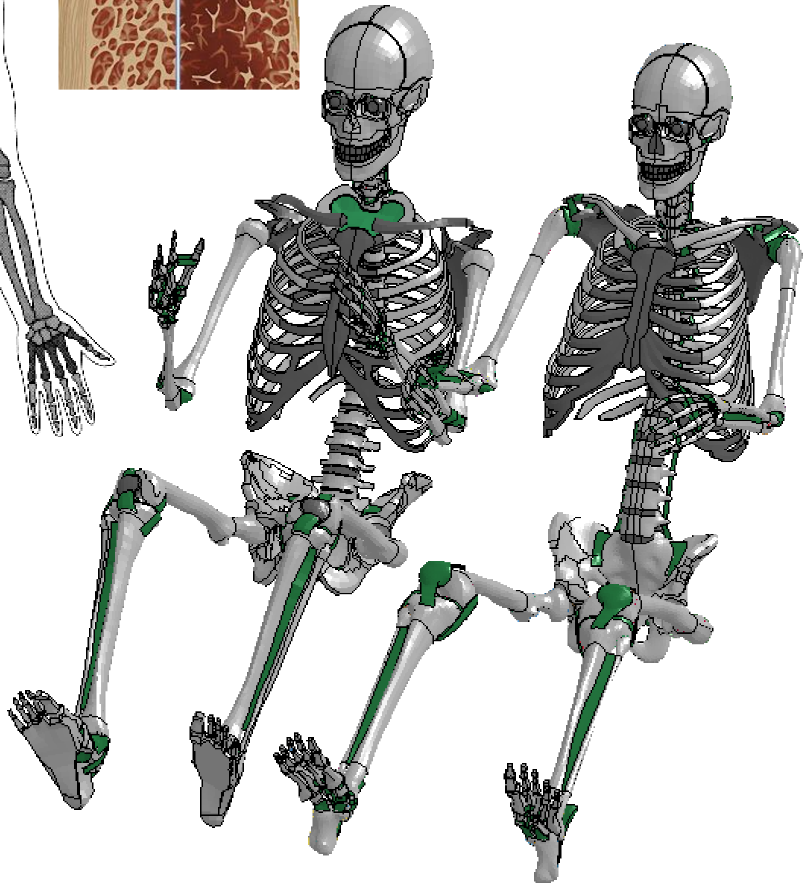
- **Problem:** Validation sources partly old and reliability/validity often unknown

THUMS Modeling Details – Skeletal Structure

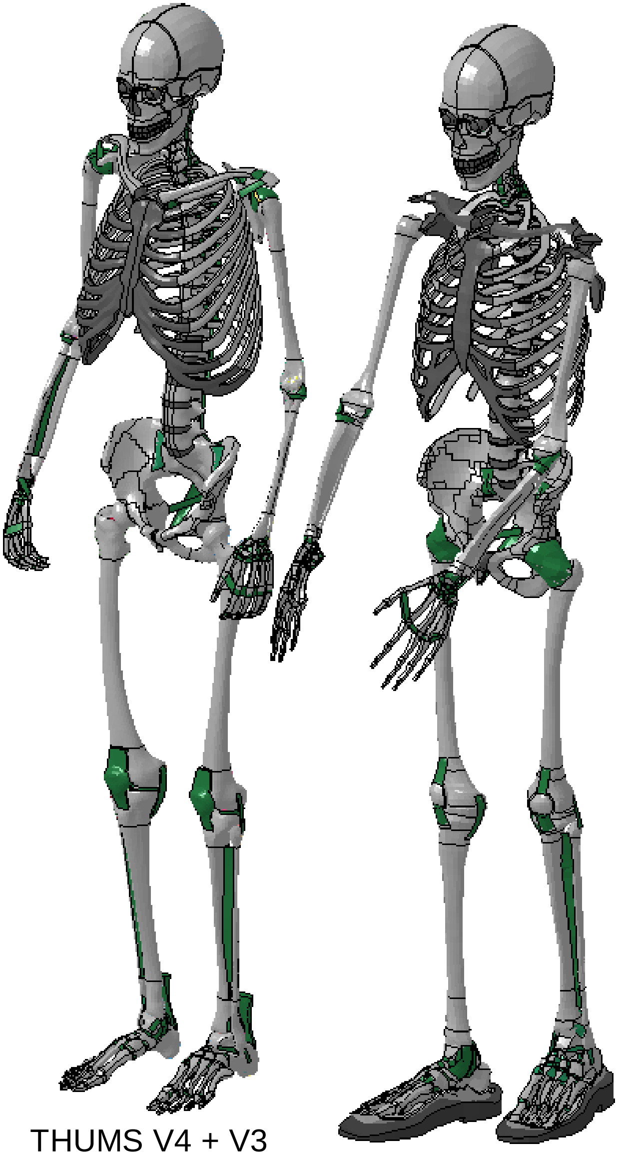




bone structure
- trabecular bones (solids)
- cortical bones (shells)

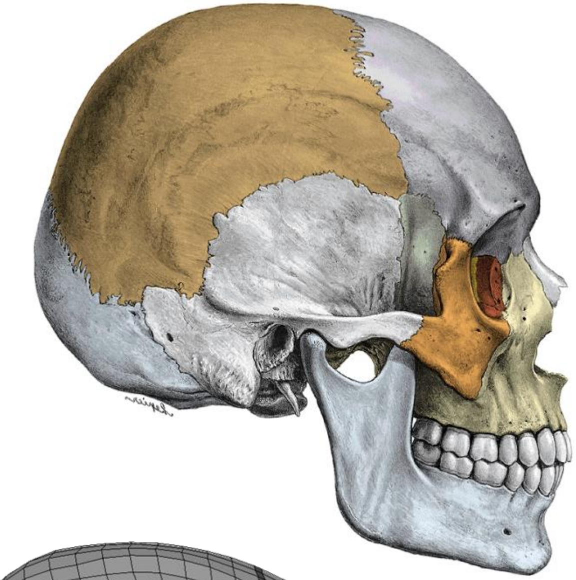


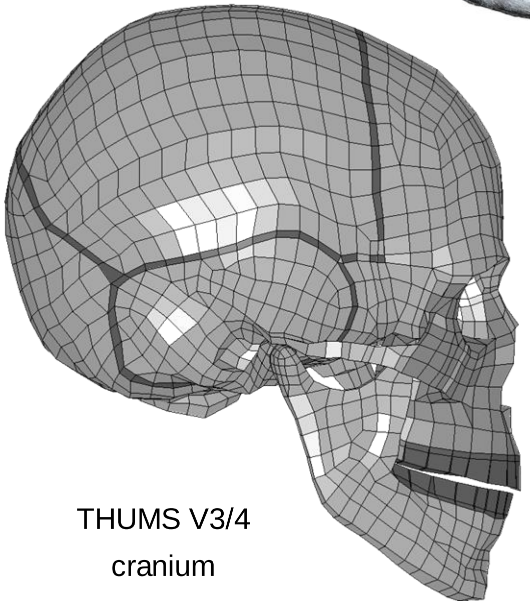
THUMS V3 + V4 occupant model



THUMS V4 + V3
pedestrian models

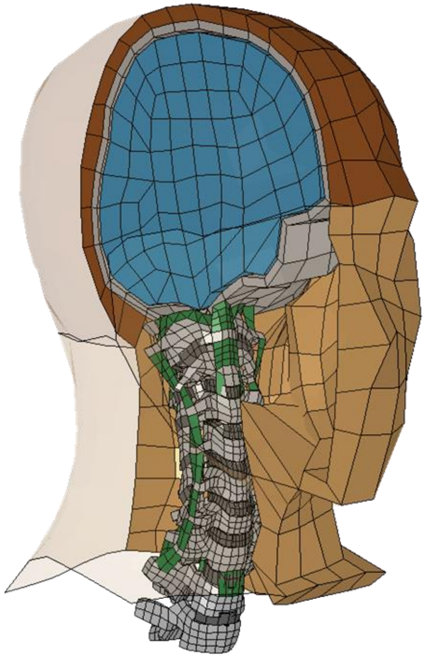
THUMS Modeling Details – Head and Cranium



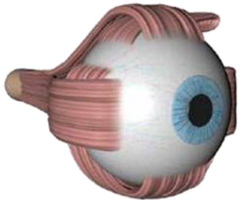


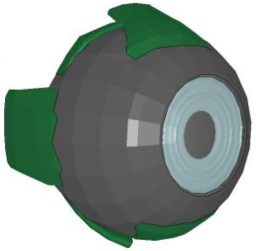
THUMS V3/4

cranium

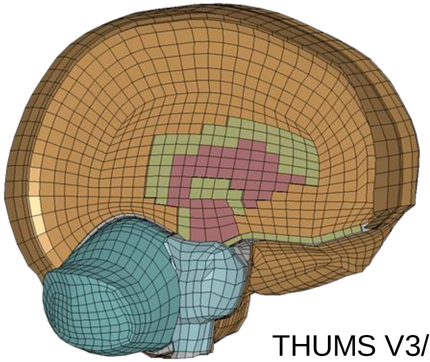


THUMS V1.x
head

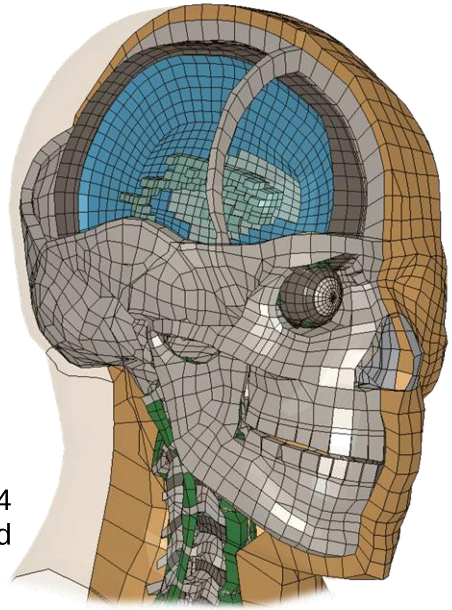




THUMS
V3/4 eye

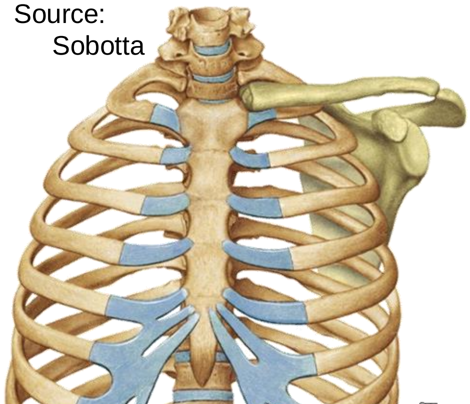


THUMS V3/4 brain

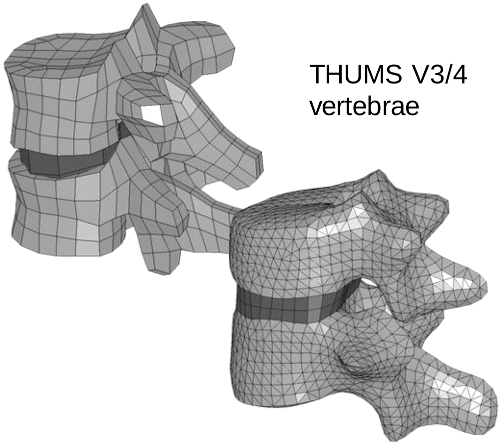


THUMS V3/4
head

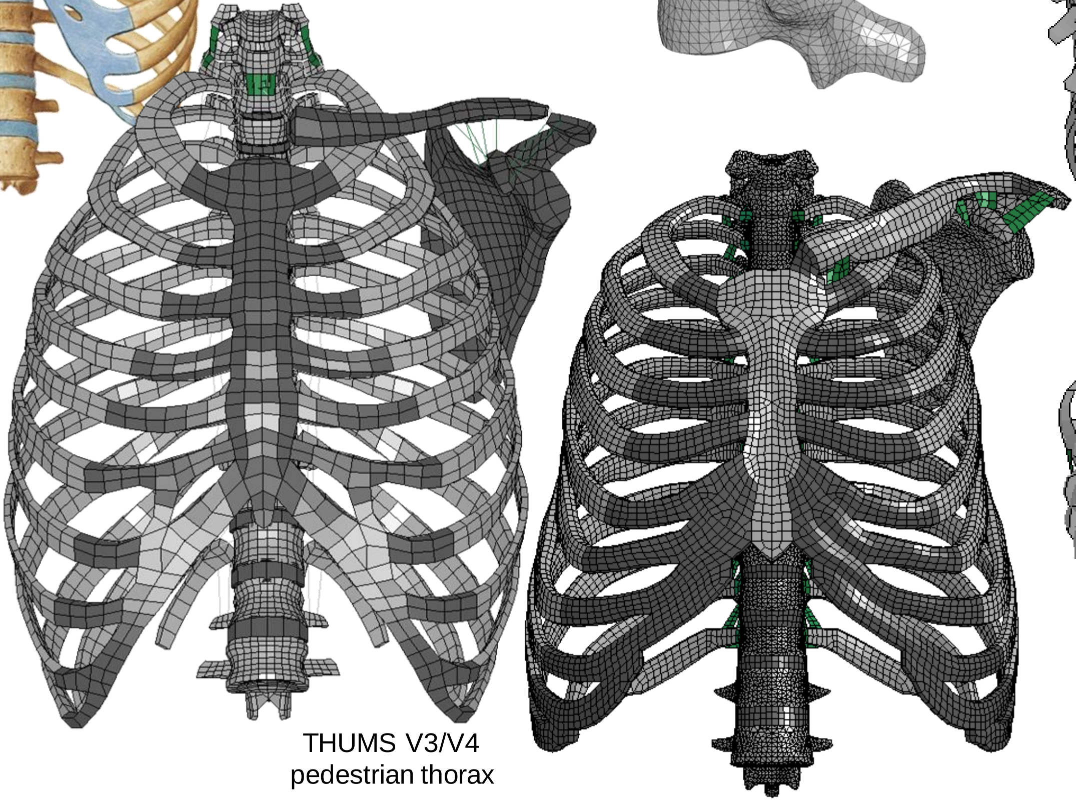
THUMS Modeling Details – Spine and Thorax



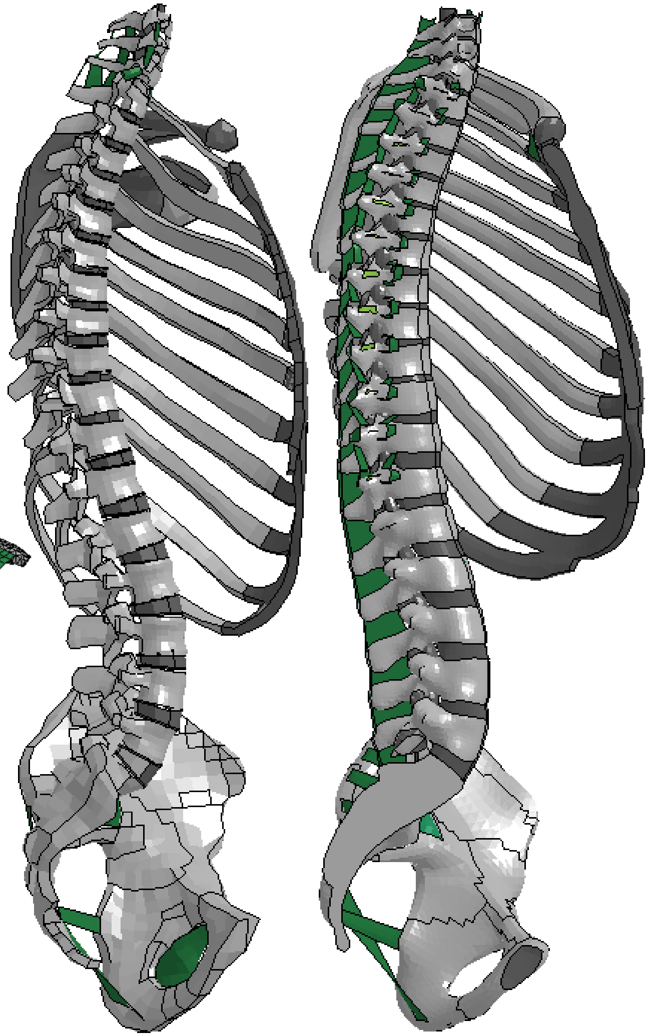
Source:
Sobotta



THUMS V3/4
vertebrae

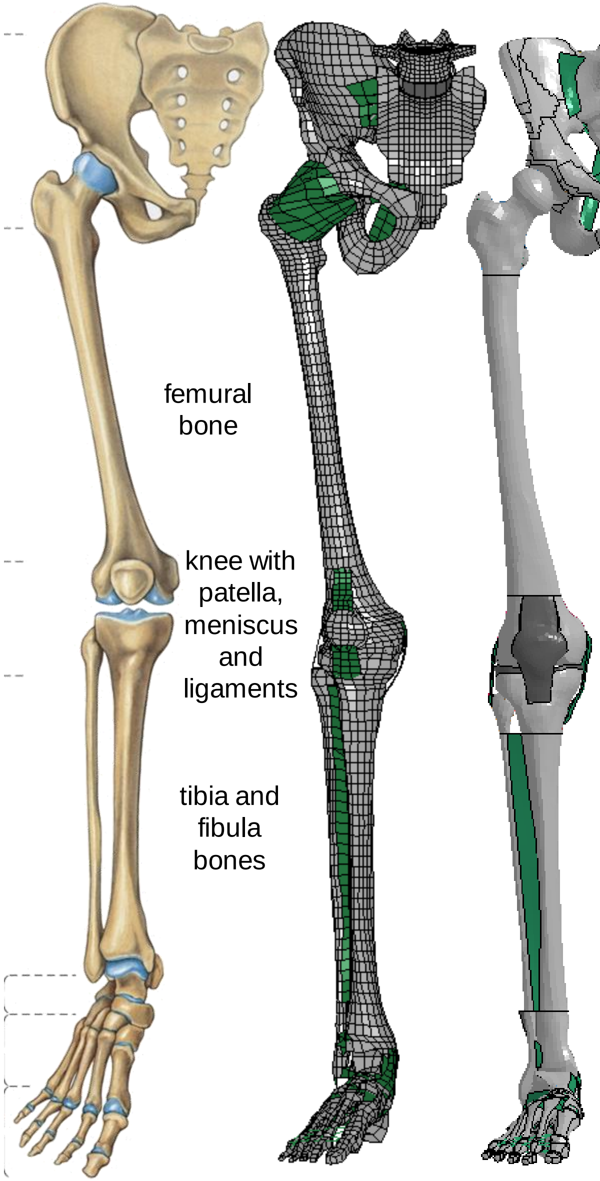


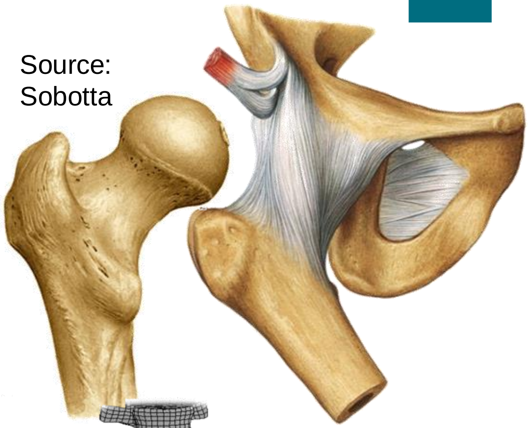
THUMS V3/V4
pedestrian thorax



THUMS V3 + V4 pedestrian
spine + thorax

THUMS Modeling Details – Lower Extremities





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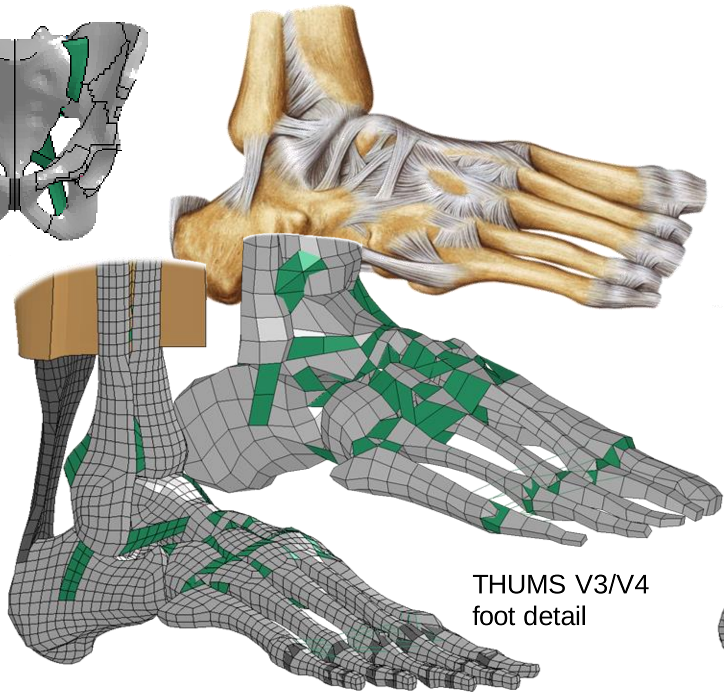
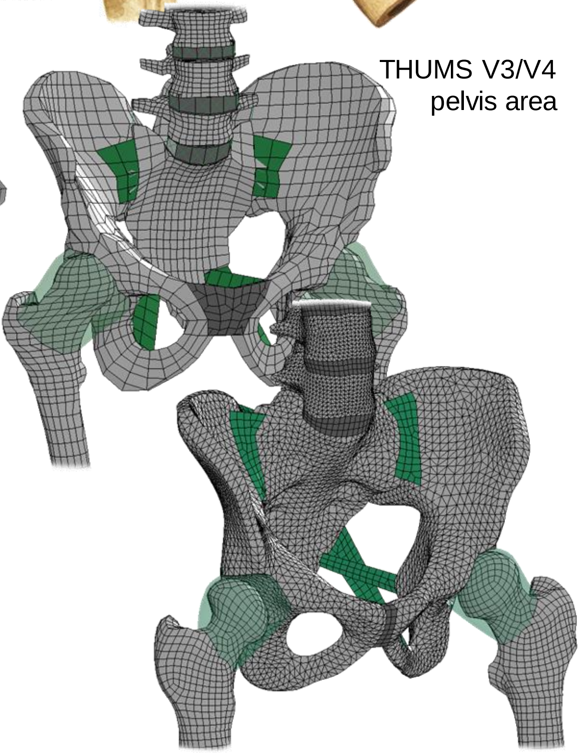
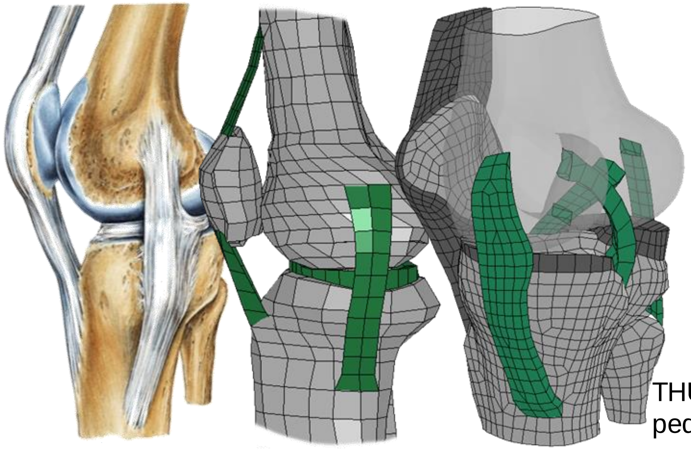


THUMS V3/V4 foot detail

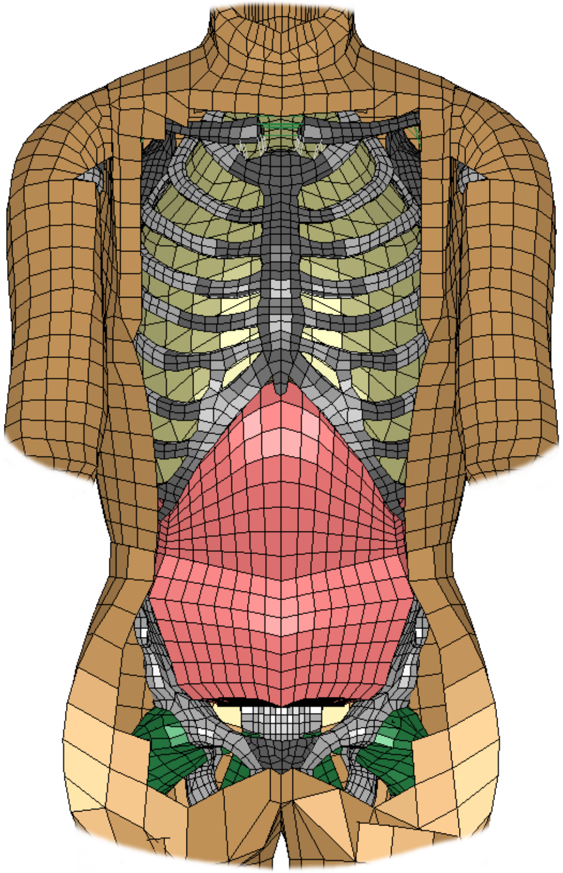


THUMS V3/V4 pelvis area

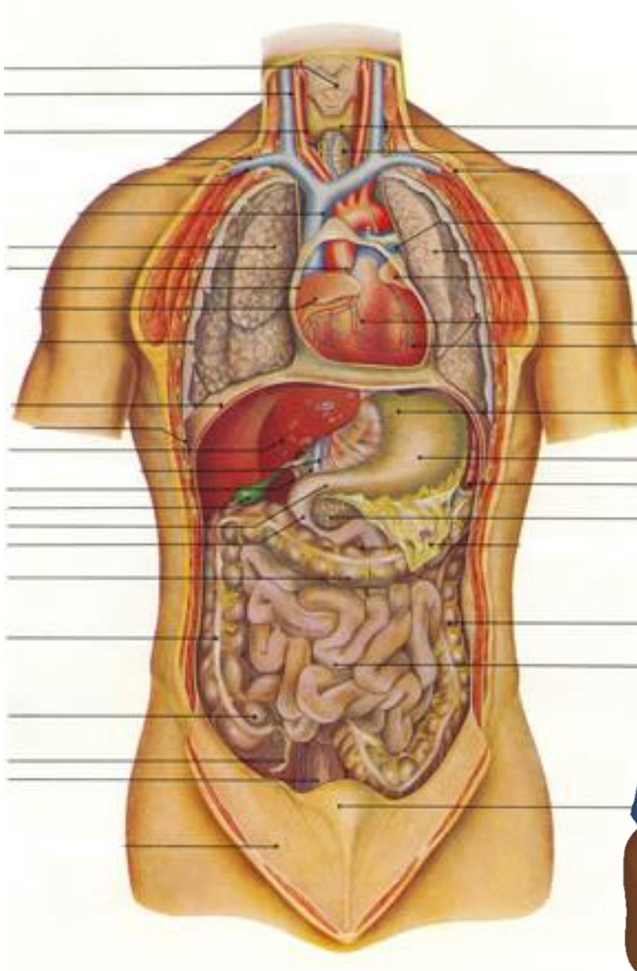


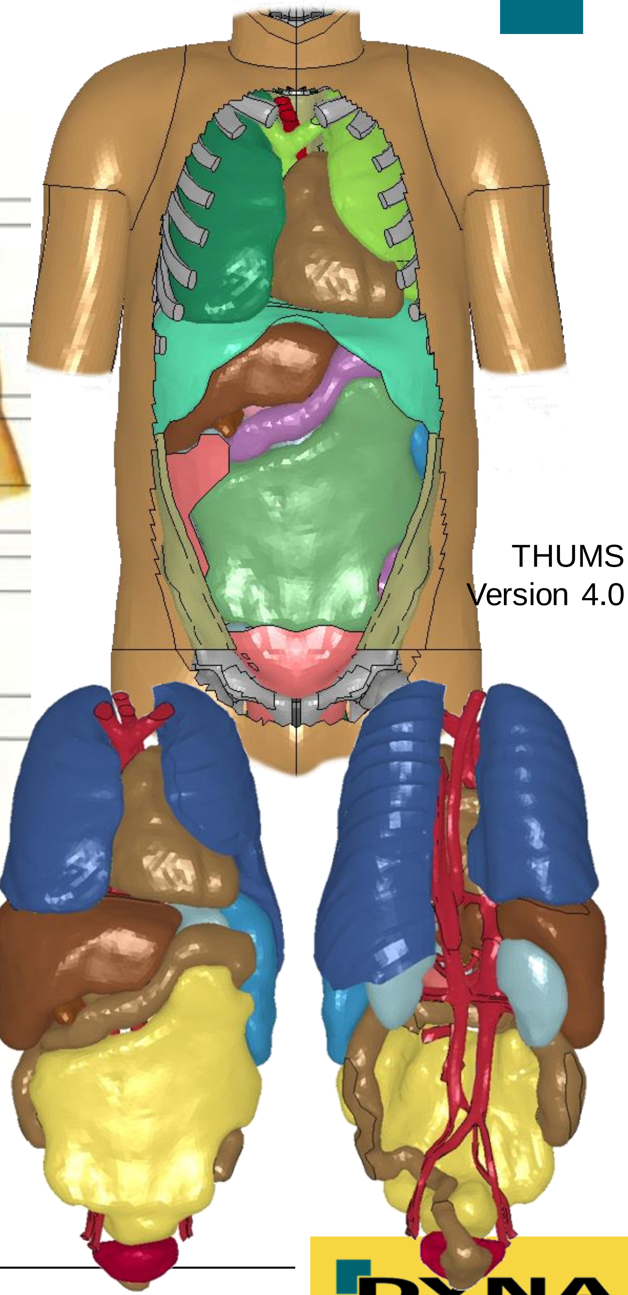
THUMS V3/v4 pedestrian knee detail

THUMS Modeling Details – Internal Organs



THUMS Version 1.x/3.0

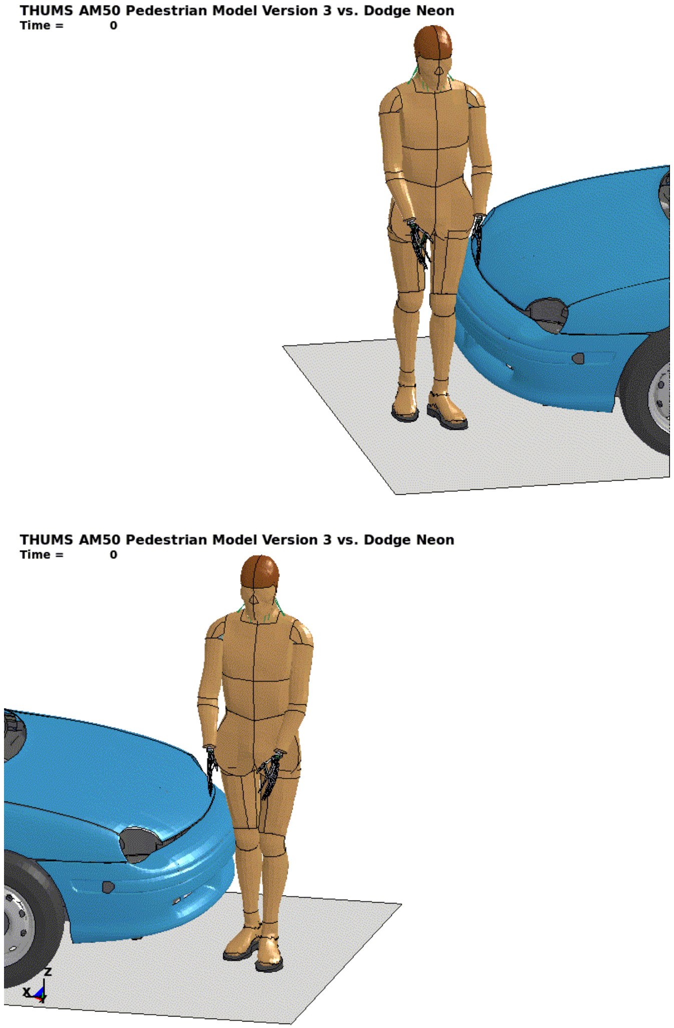




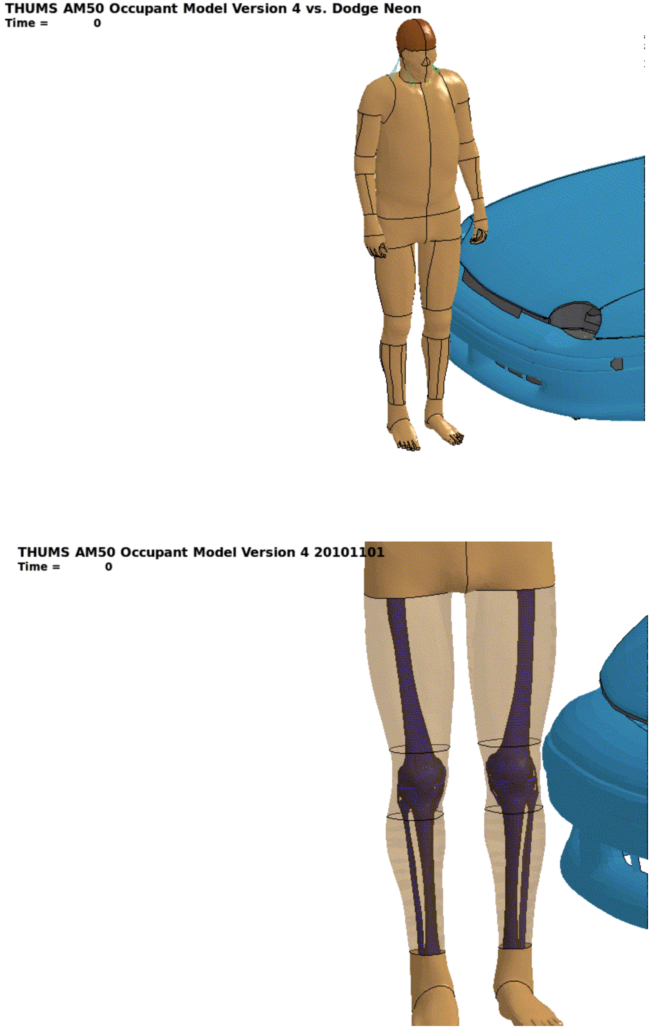
THUMS Version 4.0

- coarse organ modelling in THUMS v1.x-3.0
  - due to coarse meshing and required model stability
- (fine) organ modelling in THUMS version 4.0

Application Example – Pedestrian Model



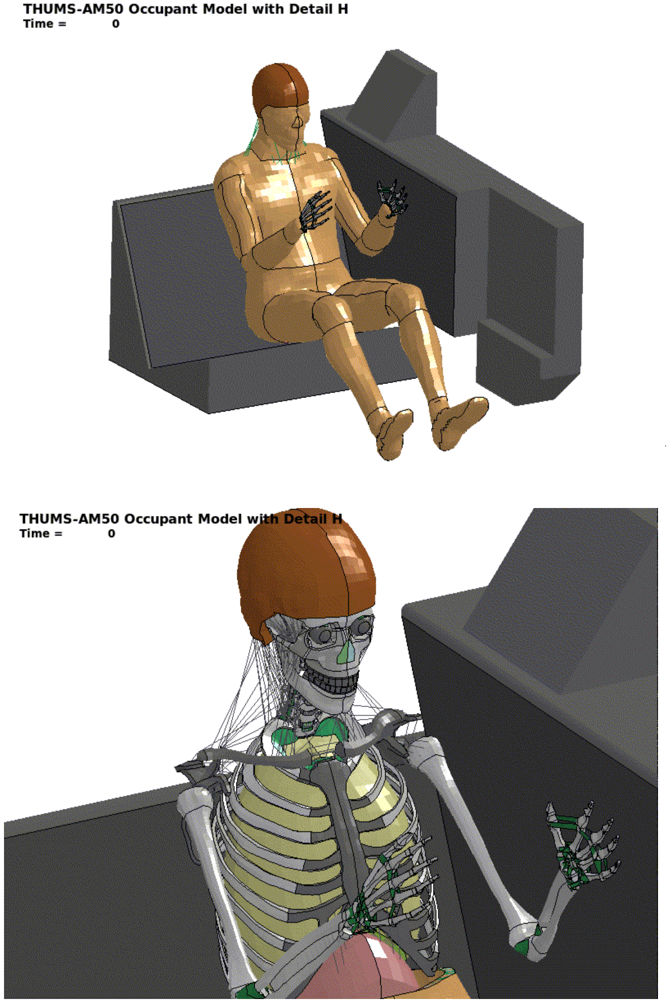
THUMS V3 from left and right side
different kinematical behaviour



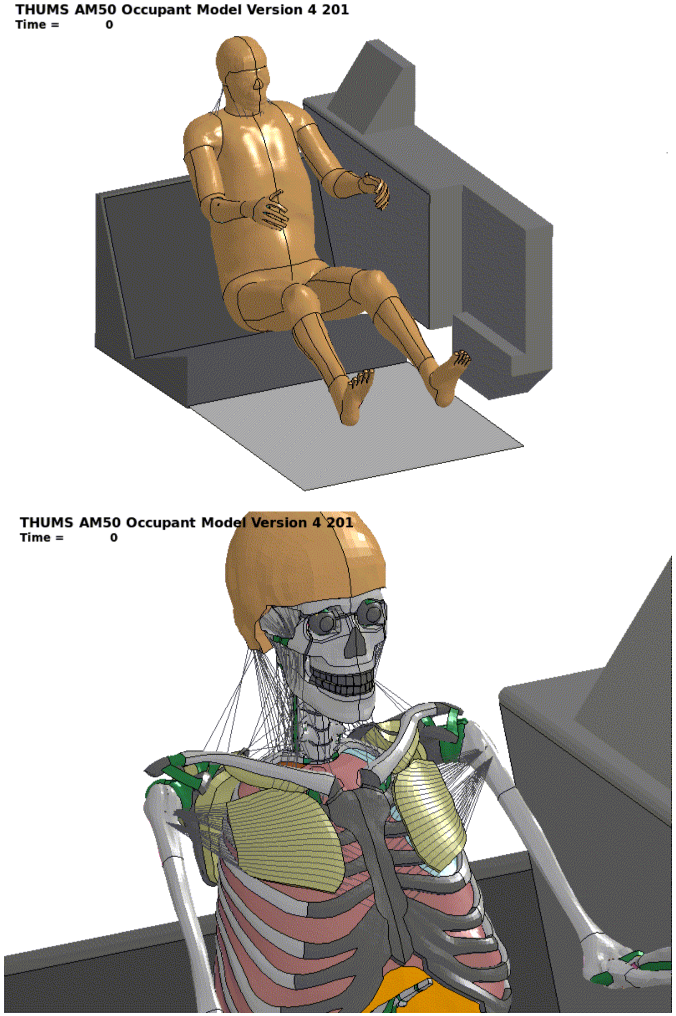
THUMS V4 left impact and zoom on
stress distribution in lower extremities

Application Example – Occupant Model

Occupant Barrier Impact – THUMS 3 vs THUMS 4



THUMS V3 impact from left total model and zoom on shoulder belt



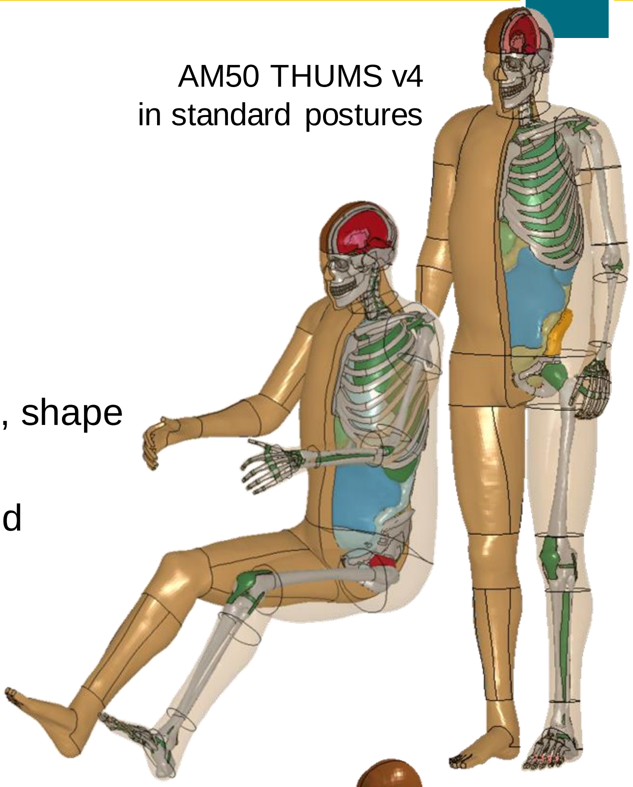
THUMS V4 impact from left total model and zoom on shoulder belt

Special Topic:

Model Shape Modification and Positioning

Model Positioning - Introduction / Motivation

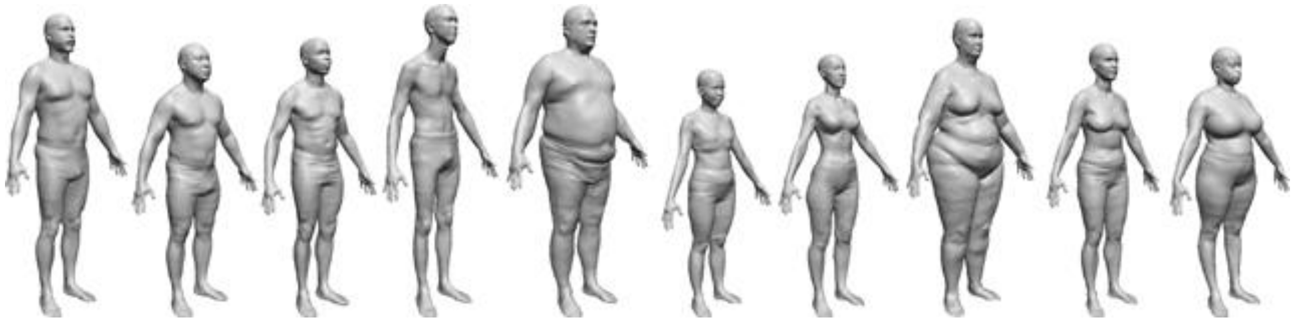
AM50 THUMS v4
in standard postures



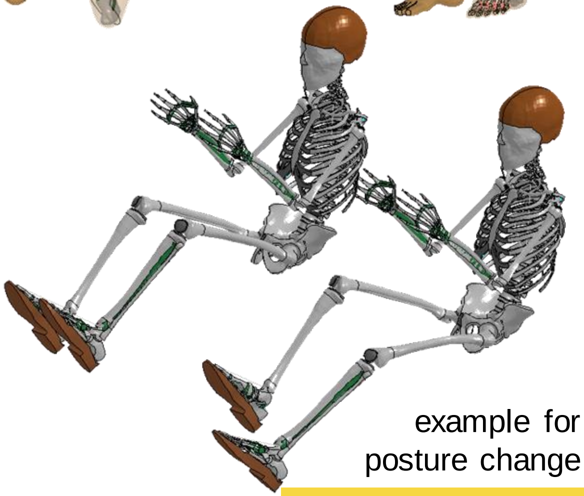
2 areas of interest

- model positioning
  - match different (non-standard) postures or seat geometries
  - necessary for virtually all load cases
- model scaling/morphing
  - human models like THUMS available only in standard body size, shape and posture (AM50, AM95, AF05, 6YO)
  - however: influence of individual body shapes is hardly accounted for (skinny/obese body shapes, changes due to ageing)
  - standard body sizes may not be representative any more
  - necessary only sometimes, combines with positioning

➢ **Q: how to quickly modify available human models to create different body shapes or postures?**



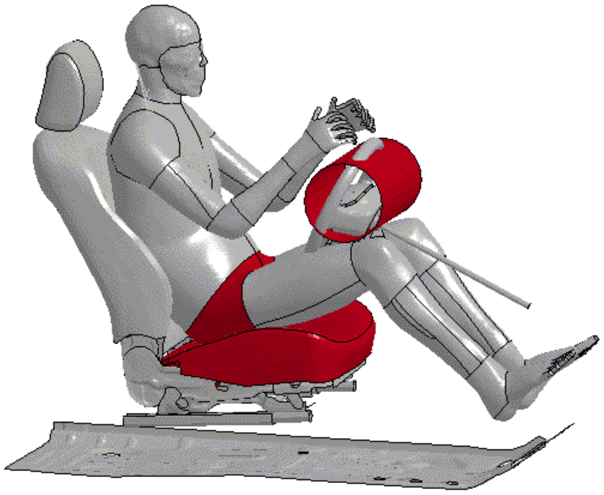
B. Allen, B. Curless, Y. Popovic: The space of human body shapes: Reconstruction and parameterization from range scans, University of Washington, 2003



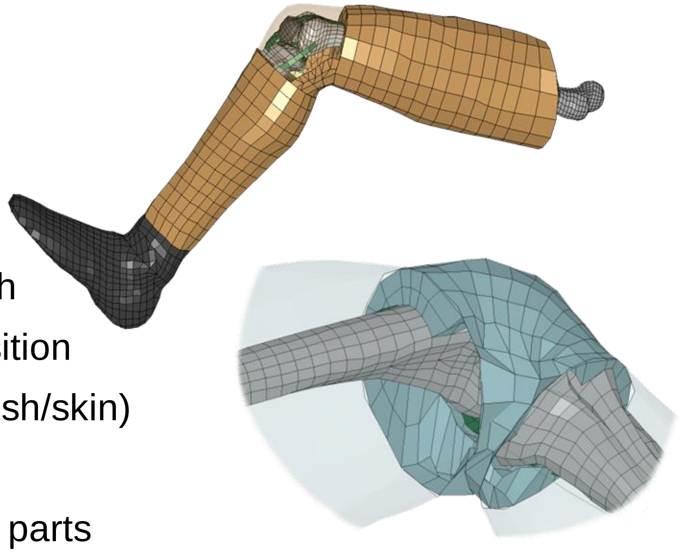
example for
posture change

Model Positioning - Introduction / Motivation

Geometric Model adaptation rather than simulations



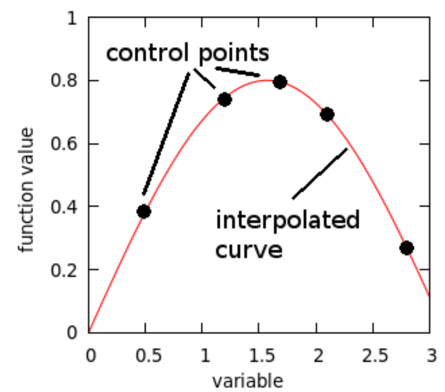
- straight forward approach: use FE simulations
  - apply appropriate boundary conditions (impactors, string pulling technique, etc.) to adapt the posture
  - perform simulations and grab desired position from the result files
  - merge new nodal coordinates into original model file
- however:
  - sometimes difficult to estimate required boundary conditions -> iterative approach
  - can be time consuming and numerically expensive
  - mesh quality deteriorates after positioning simulation -> can lead to problems in actual crash simulation



➢ use geometric smoothing procedures rather than simulations
  - based on control-point based non-linear interpolation approach
  - apply constraints – e.g. translate/rotate body limbs to final position
  - use smoothing process on interfacial parts (joints, covering flesh/skin)
  - pure relocation of nodes, no change of the mesh connectivity
  - ➢ required: smoothing procedure to adapt deformable interfacial parts

Interpolation Method – Problem Description

Mathematical Problem



- *required*: control-point based interpolation of multidimensional data with exact fit of data points
- *given*: set of *N* data points $\boldsymbol{x}_j$ ($j=1,\ldots,N$) and corresponding data values $f(\boldsymbol{x}_j)$
  - N is number of control points / landmarks
  - data points – nodal coordinates, data values – 3D displacements

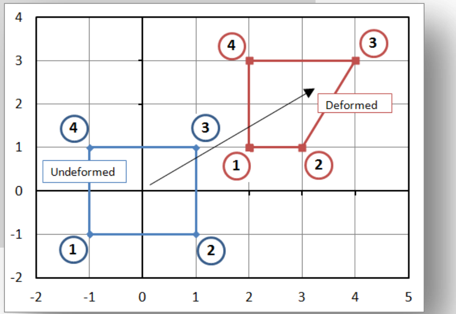
$$s(\boldsymbol{x}) = \sum_{j=1}^{N} \lambda_j \psi_j(\boldsymbol{x})$$

λ_j – interpolation weights

ψ_j – interpolation function

Example: ψ_j – linear: - N_I iso-parametric shape functions used in FE analyses

- interpolation via morphing (morphing boxes)



- only limited approximation possibilities using linear interpolation functions
- no large local deformations can be realized
- ➢ refine mesh or use higher order shape functions

- choice of interpolation function (nonlinear)
  - radial basis functions - a real-valued radially symmetric function which value only depends on the distance r to a given point
  - kriging approach - geostatistical technique, based on minimization of a Lagrangian to compute weights λ_j

Interpolation Method – Mathematical Background

Interpolation based on Radial Basis Functions

- choose

$$\psi_j = \phi(r_j), \qquad r = ||\boldsymbol{x} - \boldsymbol{x}_j||$$

- augmented RBF approach

$$s(\boldsymbol{x}) = \sum_{j=1}^{N} \lambda_j \phi(r_j) + \sum_{k=1}^{M} \gamma_k p_k(\boldsymbol{x})$$

with polynomial extension $p_k(\boldsymbol{x})$

- leads to linear equation system

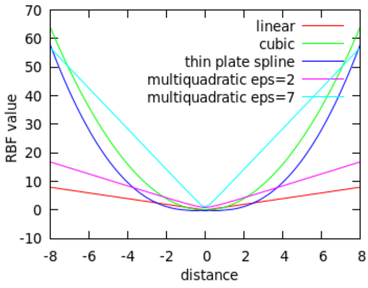
$$\begin{bmatrix} \boldsymbol{A} & \boldsymbol{P} \\ \boldsymbol{P}^T & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{\lambda} \\ \boldsymbol{\gamma} \end{bmatrix} = \begin{bmatrix} \boldsymbol{f} \\ 0 \end{bmatrix}$$

- possible radial basis functions
  - linear/cubic r, r^3
  - “thin plate spline” $r^2 \log r$
  - multiquadratic $\sqrt{1 + (\epsilon r)^2}$

➢ simple theory/implementation

➢ good results depending on polynomial extension

➢ stable system



Interpolation based on the Kriging Approach

conditions

1. minimize the scattering of the estimation error

$$\sigma_R^2 = Var\left[s^*(\boldsymbol{x}) - s(\boldsymbol{x})\right] \rightarrow \text{Min}$$

2. match of expected value

$$E\left[s^*(\boldsymbol{x})\right] = E\left[s(\boldsymbol{x})\right]$$

– minimize Lagrangian functional

$$f_l(\lambda, \mu) = \sigma_R^2(\lambda) + \sum_{k=1}^{M} \mu_k g_k(\lambda_i) \rightarrow \text{Min}$$

– leads to linear equation system for λ and μ

$$\begin{bmatrix} \boldsymbol{C} & \boldsymbol{P} \\ \boldsymbol{P}^T & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{\lambda} \\ \boldsymbol{\mu} \end{bmatrix} = \begin{bmatrix} \boldsymbol{c} \\ \boldsymbol{p} \end{bmatrix}$$

– rearrangement leads to a dual formulation:
  – matrix contains initial coordinates of control points
  – rhs contains new coordinates of control points

➢ complex theory and implementation

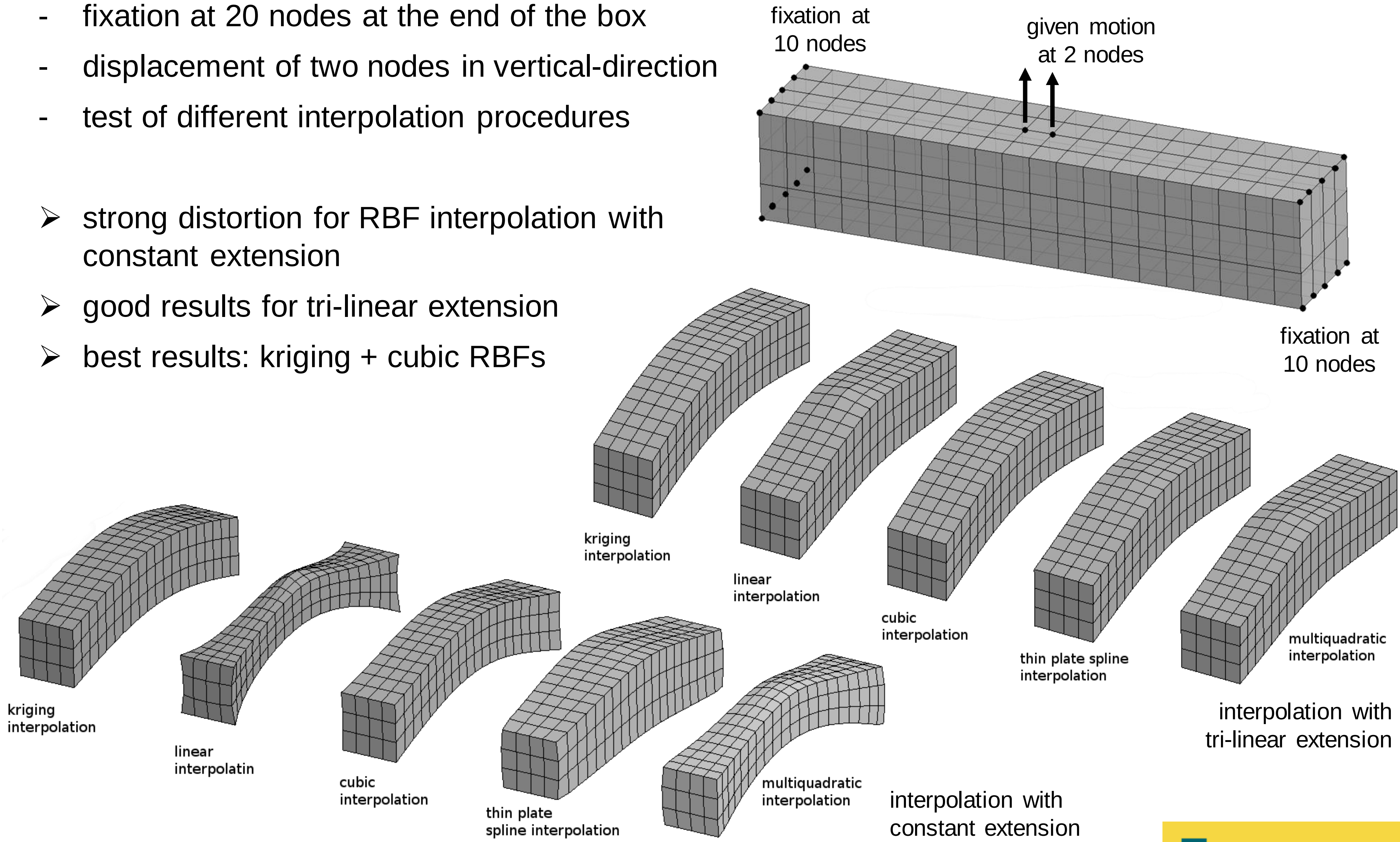
➢ very good results and stable

Interpolation Method - Example

Test Example – interpolation of a test box motion

- fixation at 20 nodes at the end of the box
- displacement of two nodes in vertical-direction
- test of different interpolation procedures

- strong distortion for RBF interpolation with constant extension
- good results for tri-linear extension
- best results: kriging + cubic RBFs



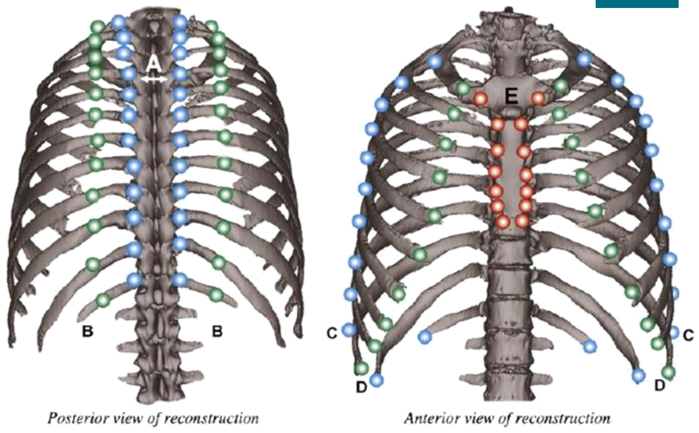
Interpolation Approach - Full Interpolation

Holistic interpolation of the Thorax

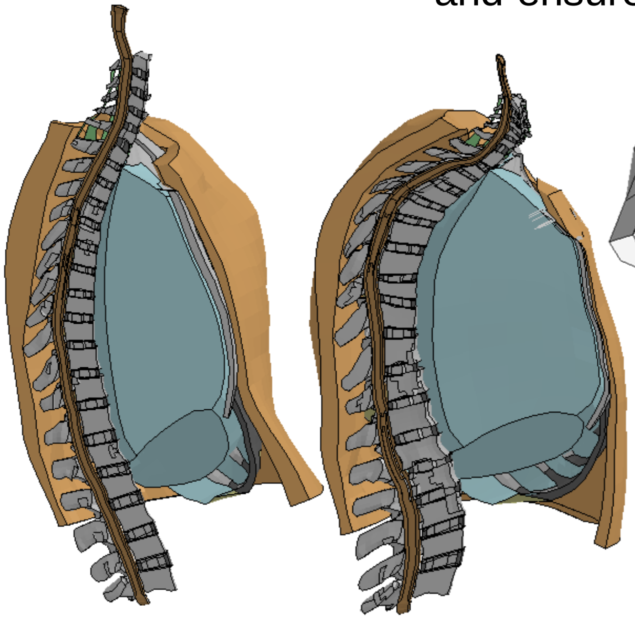
- control-point based interpolation of the whole thorax
- required
  - good distribution of control points, avoid extrapolations
  - exact match of control points necessary, otherwise local distortions -> very difficult

➢ very fast and simple method to adapt the thorax

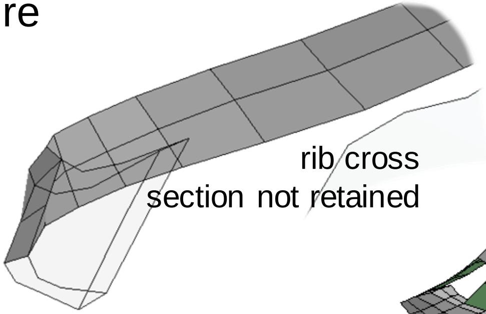
➢ however good shaped elements difficult to obtain and ensure



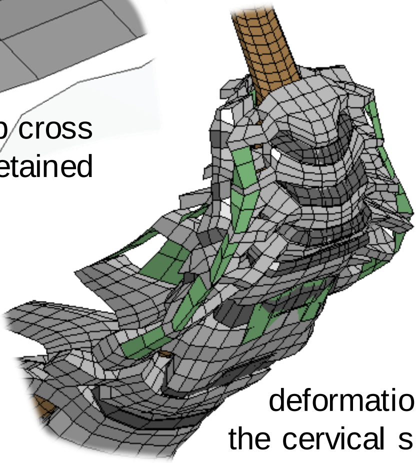
control point distribution



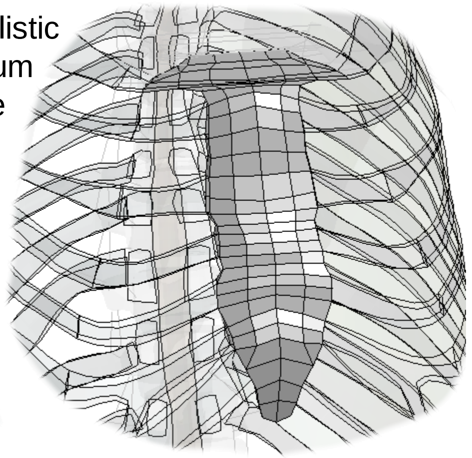
initial and interpolated THUMS thorax geometry



rib cross section not retained



deformation of the cervical spine



unrealistic sternum shape

➢ holistic interpolation hardly suitable for FE analyses

➢ unrealistic deformations / bad element shapes

➢ highly depends on distribution of control points

Interpolation Approach - Multi-Step Interpolation

- apply multistep approach to adapt the geometry in different steps

Development of an Interpolation Tool Box

- different geometric modification methods (Python)
- create batch-based geometry adaptation process

***DEFINE_SEGMENT**
define (rigid) segment to be moved or aligned

***MOVE**
move nodes/parts with optional smoothing

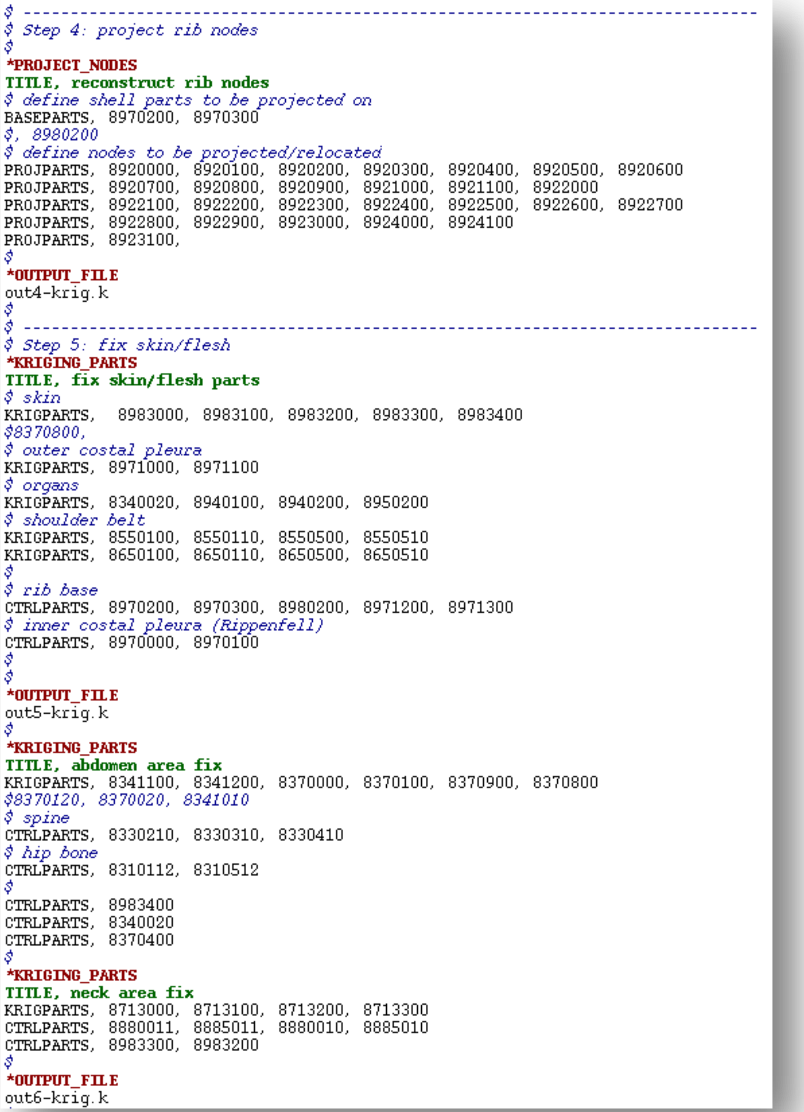
***SCALE**
scale nodes/parts with optional smoothing

***ALIGN**
align parts according to the motion of two reference points

***ALIGN_CSYS**
align parts according to the motion of a ref coordinate system

***SMOOTHING_PARTS**
smoothing of parts with given boundary conditions

***PROJECT_NODES**
project nodes to given base part and transform nodal positions



```
$ ----------------------------------------------------------------------
$ Step 4: project rib nodes
$
*PROJECT_NODES
TITLE, reconstruct rib nodes
$ define shell parts to be projected on
BASEPARTS, 8970200, 8970300
$, 8980200
$ define nodes to be projected/relocated
PROJPARTS, 8920000, 8920100, 8920200, 8920300, 8920400, 8920500, 8920600
PROJPARTS, 8920700, 8920800, 8920900, 8921000, 8921100, 8922000
PROJPARTS, 8922100, 8922200, 8922300, 8922400, 8922500, 8922600, 8922700
PROJPARTS, 8922800, 8922900, 8923000, 8924000, 8924100
PROJPARTS, 8923100,
$
*OUTPUT_FILE
out4-krig.k
$
$ ----------------------------------------------------------------------
$ Step 5: fix skin/flesh
*KRIGING_PARTS
TITLE, fix skin/flesh parts
$ skin
KRIGPARTS,  8983000, 8983100, 8983200, 8983300, 8983400
$8370800,
$ outer costal pleura
KRIGPARTS, 8971000, 8971100
$ organs
KRIGPARTS, 8340020, 8940100, 8940200, 8950200
$ shoulder belt
KRIGPARTS, 8550100, 8550110, 8550500, 8550510
KRIGPARTS, 8650100, 8650110, 8650500, 8650510
$
$ rib base
CTRLPARTS, 8970200, 8970300, 8980200, 8971200, 8971300
$ inner costal pleura (Rippenfell)
CTRLPARTS, 8970000, 8970100
$
$
*OUTPUT_FILE
out5-krig.k
$
*KRIGING_PARTS
TITLE, abdomen area fix
KRIGPARTS, 8341100, 8341200, 8370000, 8370100, 8370900, 8370800
$8370120, 8370020, 8341010
$ spine
CTRLPARTS, 8330210, 8330310, 8330410
$ hip bone
CTRLPARTS, 8310112, 8310512
$
CTRLPARTS, 8983400
CTRLPARTS, 8340020
CTRLPARTS, 8370400
$
*KRIGING_PARTS
TITLE, neck area fix
KRIGPARTS, 8713000, 8713100, 8713200, 8713300
CTRLPARTS, 8880011, 8885011, 8880010, 8885010
CTRLPARTS, 8983300, 8983200
$
*OUTPUT_FILE
out6-krig.k
```

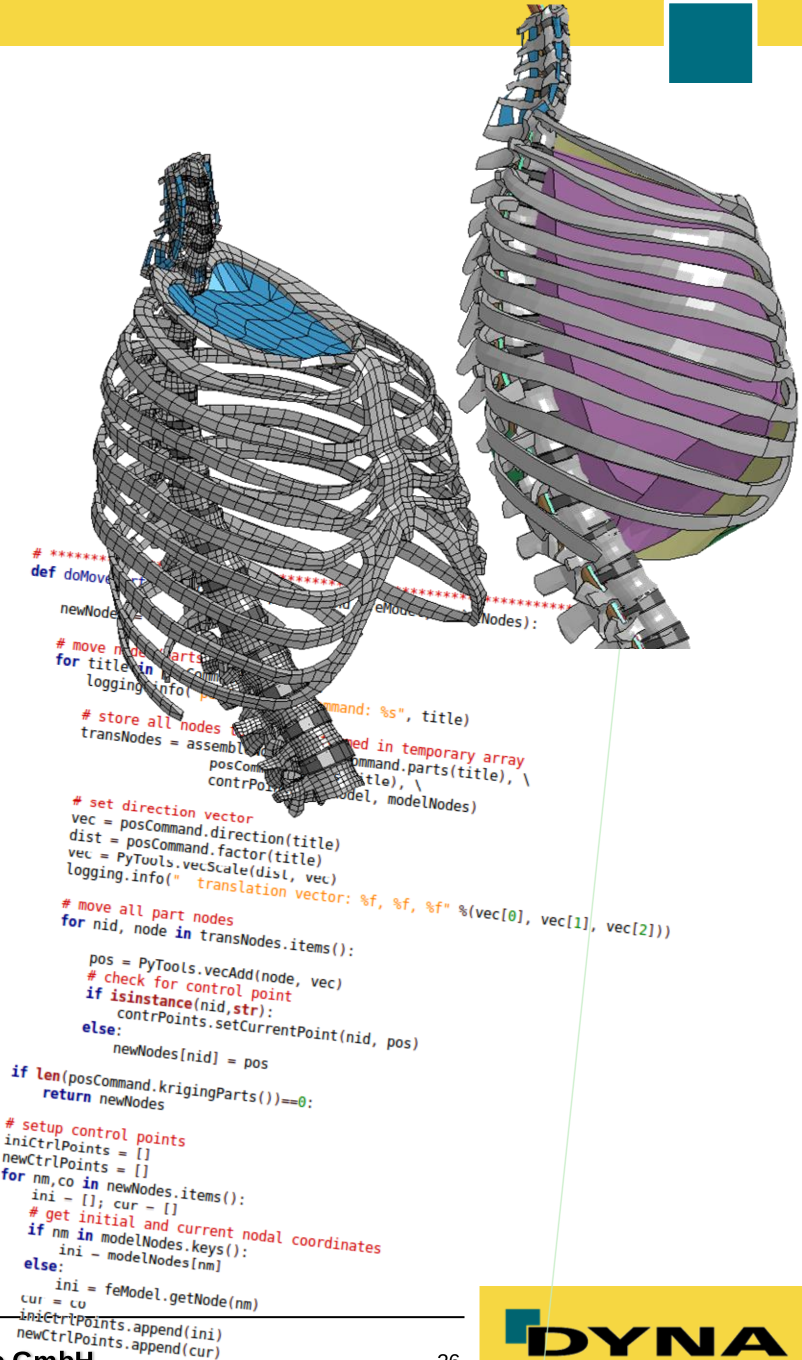
Multi-Step Thorax Interpolation

Multistep Interpolation of the Thorax

- here: simplified parameterization of the thorax
  - statistic evaluation of a CT database
  - given: fix of sternum position and shape
  - given: thorax width in each rib plane
  - assumption: no spine deformation

➢ automatic geometry adaptation using tool box

- adaptation in 7 steps
  1. sternum position and shape (given)
  2. adaptation of rib base
  3. fix thorax width (given)
  4. reconstruct ribs (keep thickness and shape)
  5. thoracic skin, flesh and organs
  6. transitions to head, pelvis/abdomen
  7. model fixes: remove contact penetrations, element distortions etc.

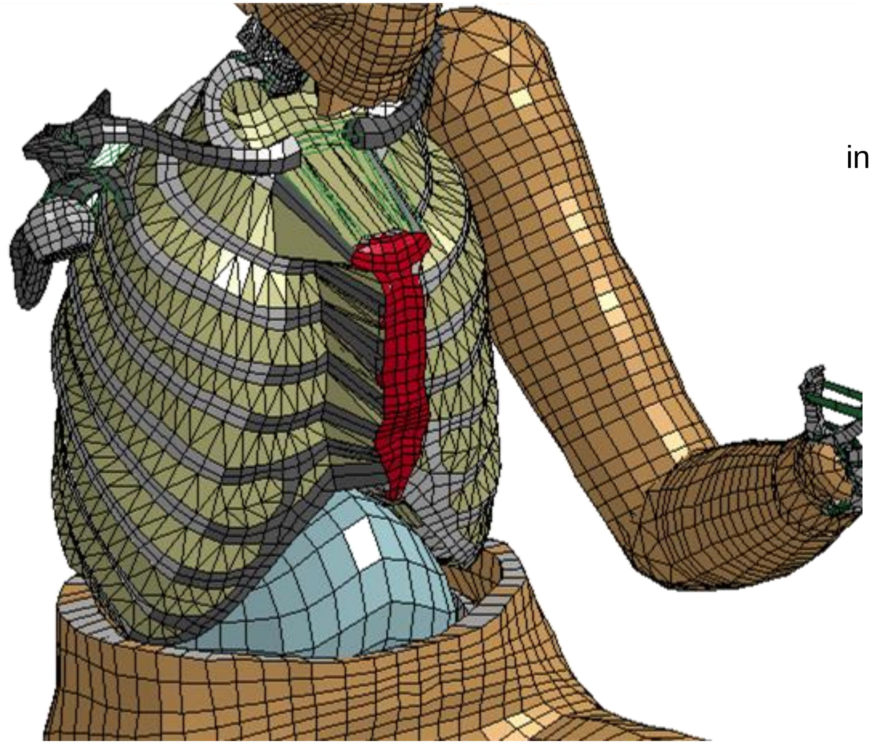


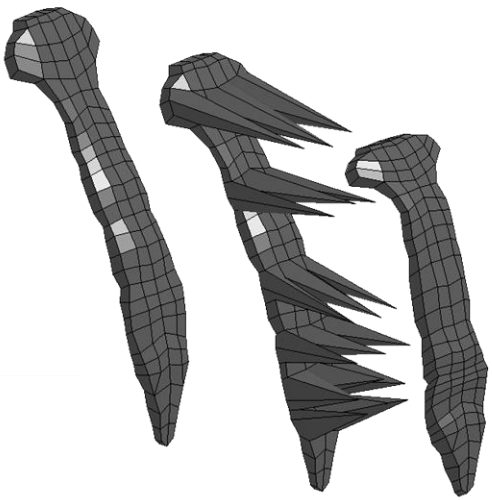
```
# *******                    ***********************************
def doMove                          eMode            Nodes):

    newNode

    # move n de  arts
    for title in      Comm
        logging info(  p               mmand: %s", title)

        # store all nodes t                   ned in temporary array
        transNodes = assembl                 ommand.parts(title), \
                         posCom                     itle), \
                         contrPoi                  odel, modelNodes)
        # set direction vector
        vec = posCommand.direction(title)
        dist = posCommand.factor(title)
        vec = PyTools.vecScale(dist, vec)
        logging.info("  translation vector: %f, %f, %f" %(vec[0], vec[1], vec[2]))

        # move all part nodes
        for nid, node in transNodes.items():

            pos = PyTools.vecAdd(node, vec)
            # check for control point
            if isinstance(nid,str):
                contrPoints.setCurrentPoint(nid, pos)
            else:
                newNodes[nid] = pos

    if len(posCommand.krigingParts())==0:
        return newNodes

    # setup control points
    iniCtrlPoints = []
    newCtrlPoints = []
    for nm,co in newNodes.items():
        ini = []; cur = []
        # get initial and current nodal coordinates
        if nm in modelNodes.keys():
            ini = modelNodes[nm]
        else:
            ini = feModel.getNode(nm)
        cur = co
        iniCtrlPoints.append(ini)
        newCtrlPoints.append(cur)
```

Multi-Step Thorax Interpolation

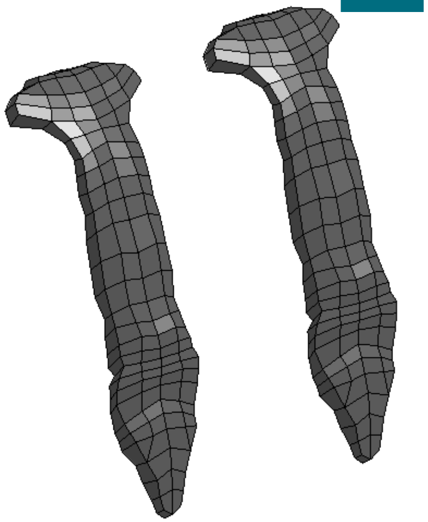
Step 1 – Adaptation of Sternum

- given: points of sternum (s1-s7)
  - describe sternum position and shape
- motion of sternum points and smoothing process

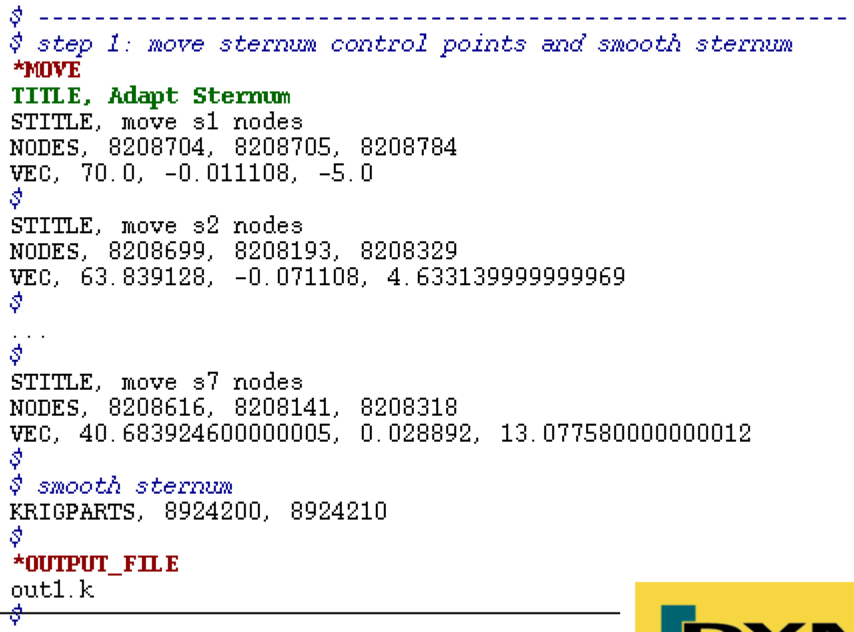




initial and adapted geometry



comparison
RBF (cubic) and kriging

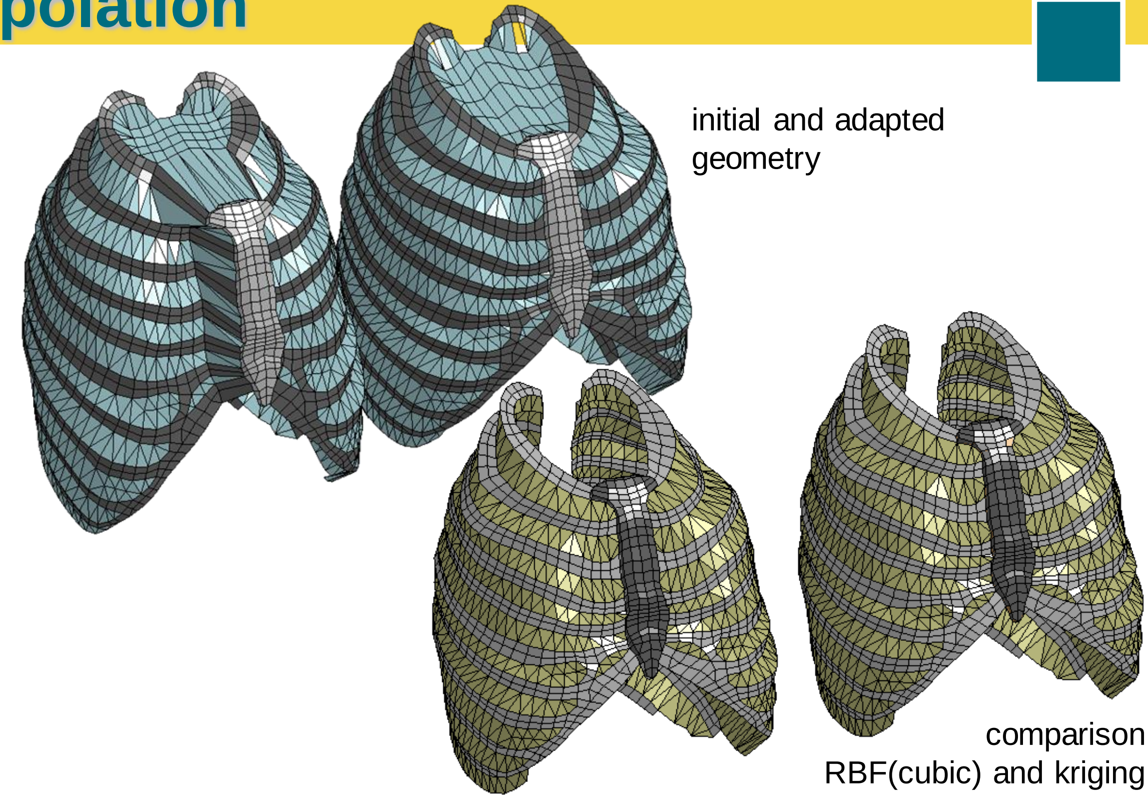


```
$ ------------------------------------------------------------
$ step 1: move sternum control points and smooth sternum
*MOVE
TITLE, Adapt Sternum
STITLE, move s1 nodes
NODES, 8208704, 8208705, 8208784
VEC, 70.0, -0.011108, -5.0
$
STITLE, move s2 nodes
NODES, 8208699, 8208193, 8208329
VEC, 63.839128, -0.071108, 4.633139999999969
$
...
$
STITLE, move s7 nodes
NODES, 8208616, 8208141, 8208318
VEC, 40.683924600000005, 0.028892, 13.077580000000012
$
$ smooth sternum
KRIGPARTS, 8924200, 8924210
$
*OUTPUT_FILE
out1.k
$
```

Multi-Step Thorax Interpolation

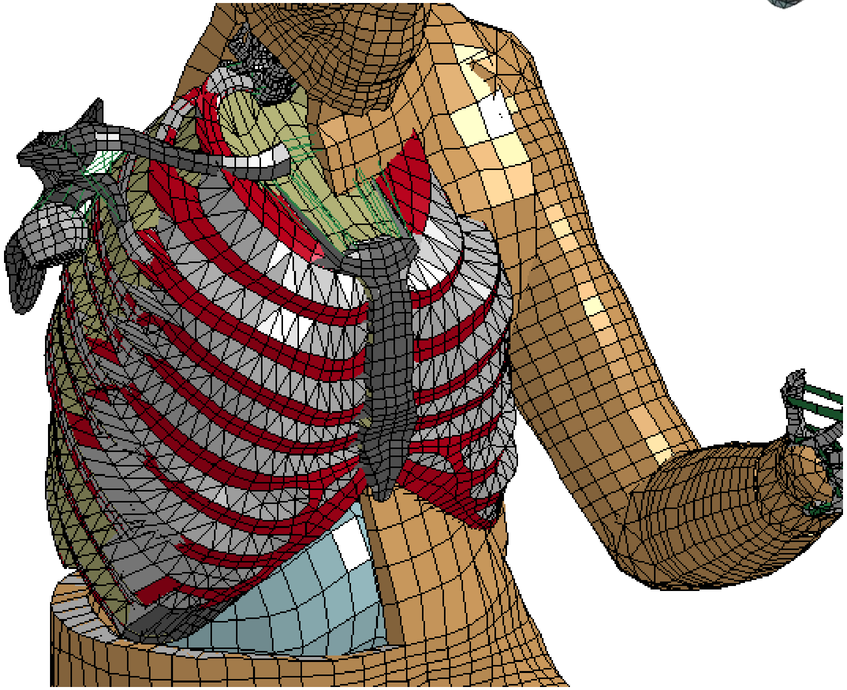
Step 2 – Adaptation of Rib Basis

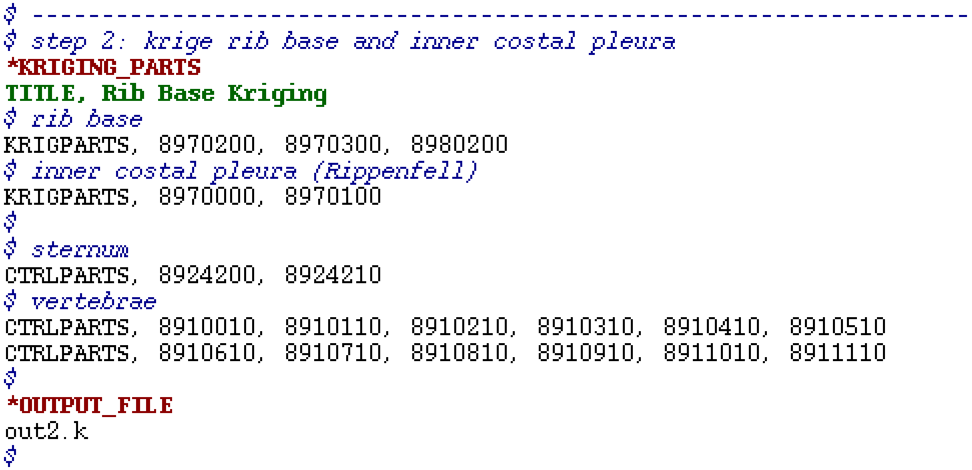
- given: sternum motion
- interpolation of rib basis and inner costal pleura
- sternum and vertebrae as control parts (boundary conditions)



initial and adapted geometry

comparison RBF(cubic) and kriging



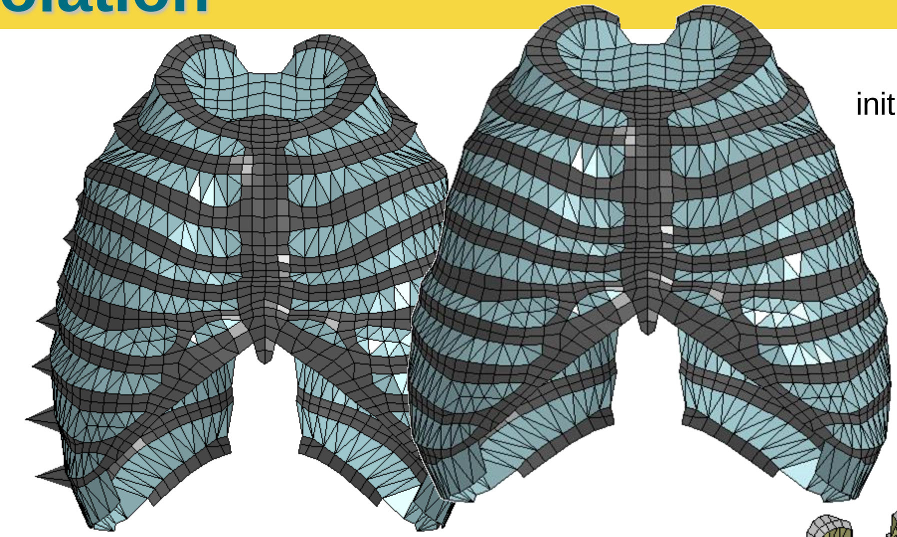


```
$ ----------------------------------------------------------------------
$ step 2: krige rib base and inner costal pleura
*KRIGING_PARTS
TITLE, Rib Base Kriging
$ rib base
KRIGPARTS, 8970200, 8970300, 8980200
$ inner costal pleura (Rippenfell)
KRIGPARTS, 8970000, 8970100
$
$ sternum
CTRLPARTS, 8924200, 8924210
$ vertebrae
CTRLPARTS, 8910010, 8910110, 8910210, 8910310, 8910410, 8910510
CTRLPARTS, 8910610, 8910710, 8910810, 8910910, 8911010, 8911110
$
*OUTPUT_FILE
out2.k
$
```

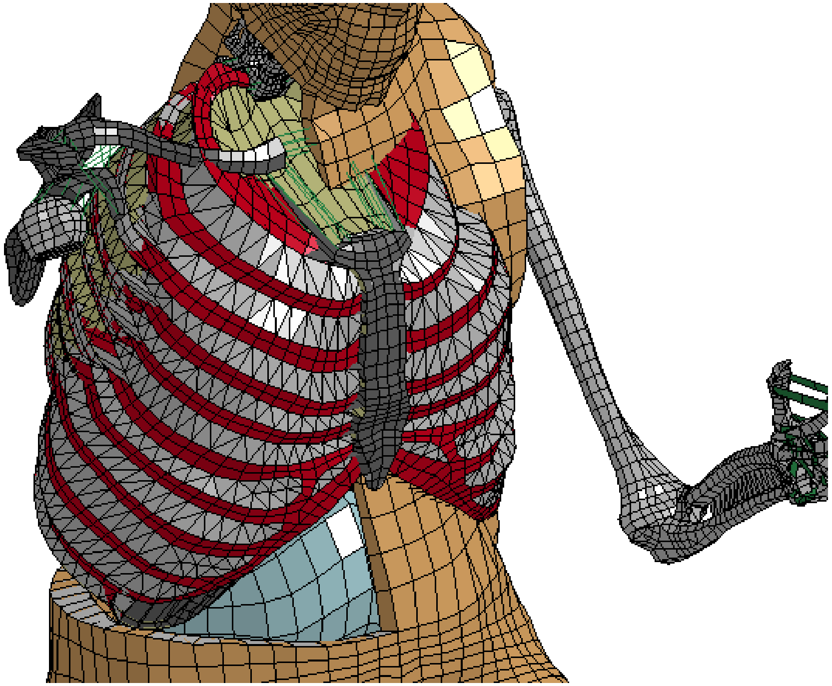
Multi-Step Thorax Interpolation

Step 3 – Fix of thorax width

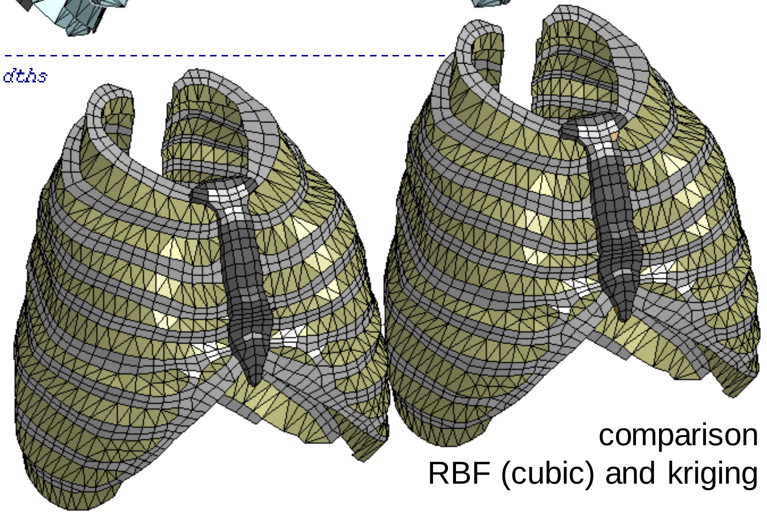
- given: new rib basis + sternum
- adaptation of thorax in each rib plane (nodal displacements)
- interpolation of rib basis and inner costal pleura, sternum and vertebrae as control points



initial and adapted geometry



```
$ ------------------------------------------------------------------
$ step 3: adapt rib widths
*MOVE
TITLE, fix rib widths
$
STITLE, rib s1 right
NODES, 8204699
VEC, 0.0, -7.82, 0.0
$
STITLE, rib s1 left
NODES, 8206381
VEC, 0.0, 7.82, 0.0
$
...
$
STITLE, rib s10 right
NODES, 8206103
VEC, 0.0, -23.32, 0.0
$
STITLE, rib s10 left
NODES, 8207785
VEC, 0.0, 23.32, 0.0
$
$ rib base
KRIGPARTS, 8970200, 8970300, 8980200
$ inner costal pleura (Rippenfell)
KRIGPARTS, 8970000, 8970100
$ sternum
CTRLPARTS, 8924200, 8924210
$ vertebrae
CTRLPARTS, 8910010, 8910110, 8910210, 8910310, 8910410, 8910510
CTRLPARTS, 8910610, 8910710, 8910810, 8910910, 8911010, 8911110
$
*OUTPUT_FILE
out3.k
$
```

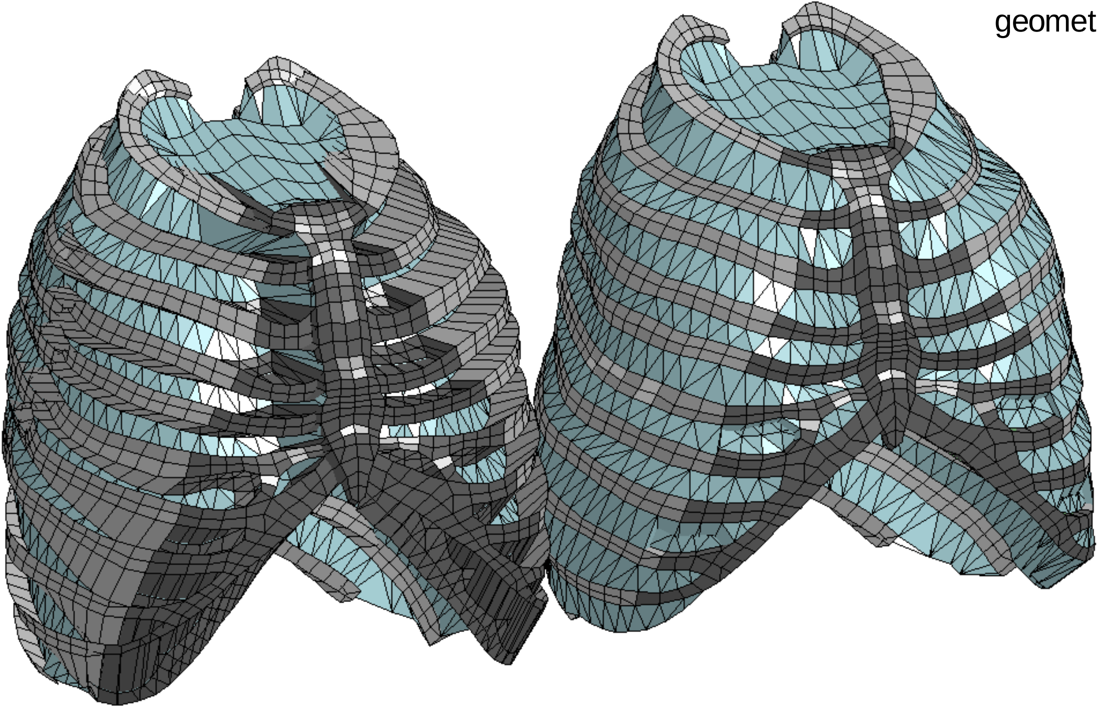


comparison
RBF (cubic) and kriging

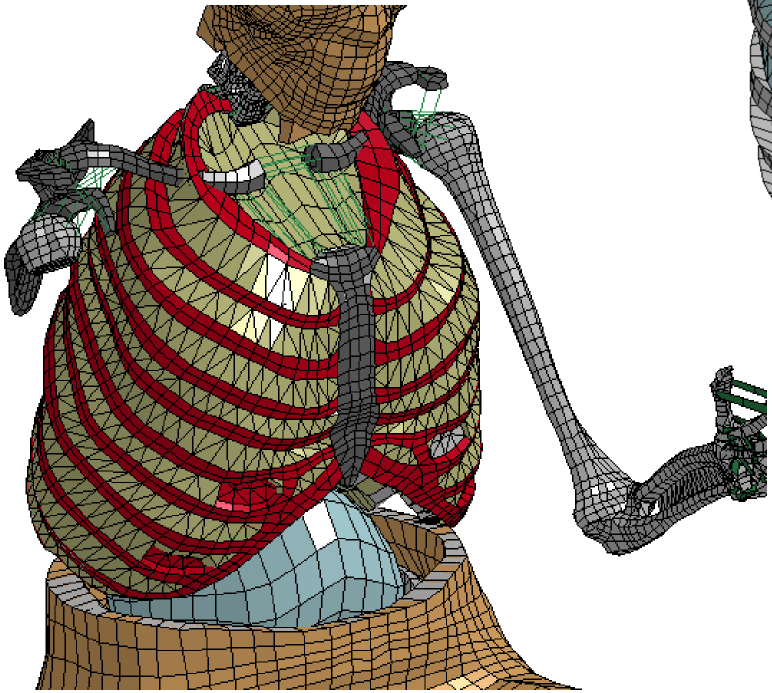
Multi-Step Thorax Interpolation

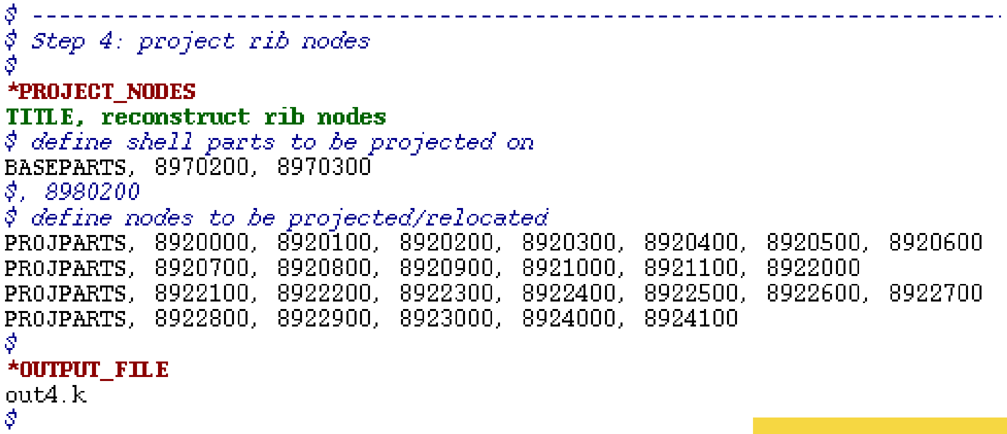
Step 4 – Reconstruction of Rib Geometry

- given: new rib base and sternum
- reconstruction of rib
    - projection of “old” rib onto rib base and reconstruction on “new” rib base
- minimize of rib deformation
- retain rib cross section



initial and adapted geometry



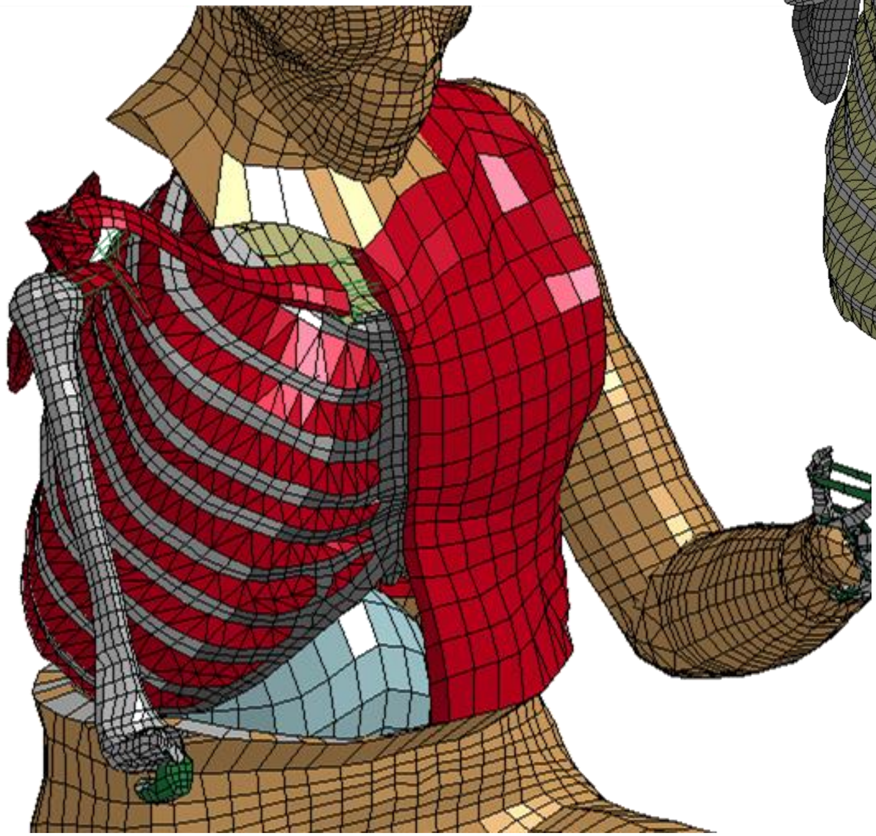


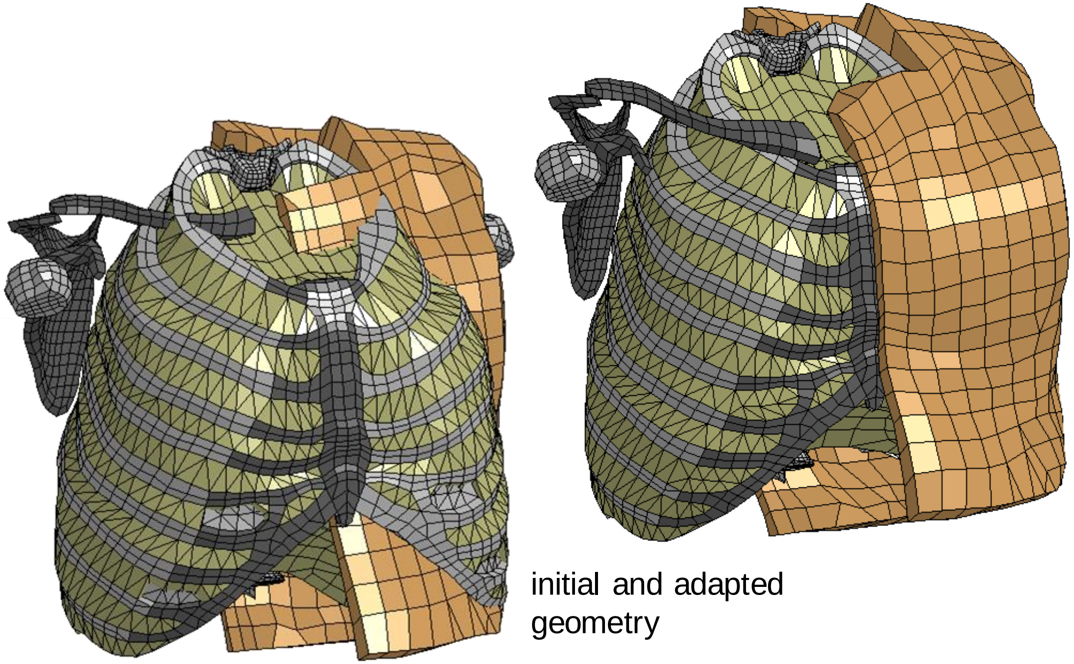
```
$ -------------------------------------------------------------------------
$ Step 4: project rib nodes
$
*PROJECT_NODES
TITLE, reconstruct rib nodes
$ define shell parts to be projected on
BASEPARTS, 8970200, 8970300
$, 8980200
$ define nodes to be projected/relocated
PROJPARTS, 8920000, 8920100, 8920200, 8920300, 8920400, 8920500, 8920600
PROJPARTS, 8920700, 8920800, 8920900, 8921000, 8921100, 8922000
PROJPARTS, 8922100, 8922200, 8922300, 8922400, 8922500, 8922600, 8922700
PROJPARTS, 8922800, 8922900, 8923000, 8924000, 8924100
$
*OUTPUT_FILE
out4.k
$
```

Multi-Step Thorax Interpolation

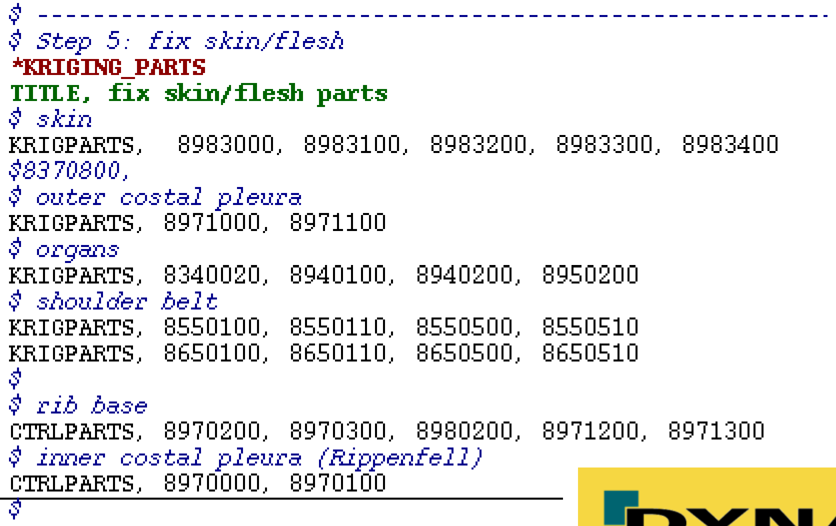
Step 5 – Adaptation of the Thorax (flesh, skin, organs, shoulder belt)

- given: new rib, sternum and vertebrae
- adaptation of skin, flesh, organs and shoulder belt using kriging
- rib base and costal pleura as control parts





initial and adapted geometry

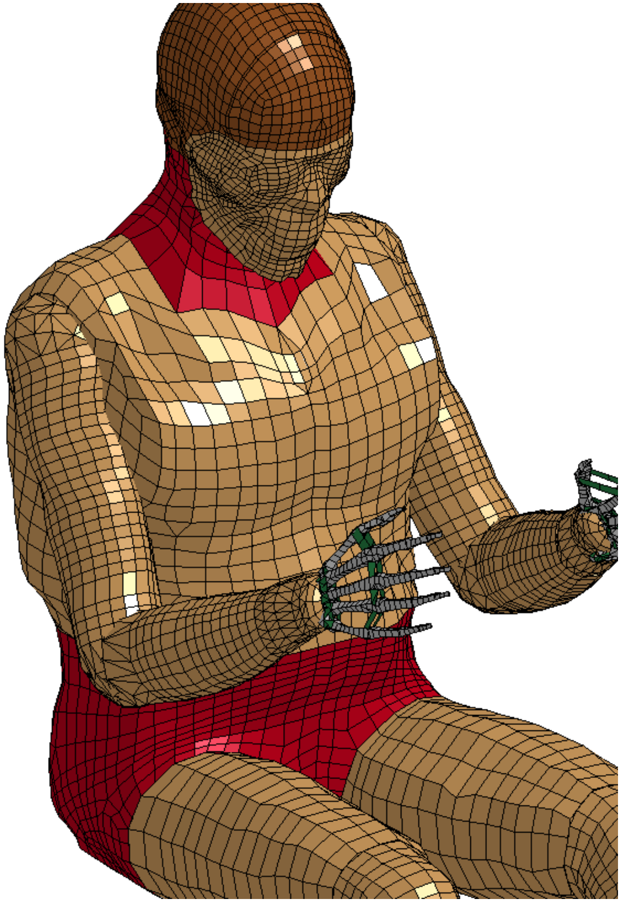


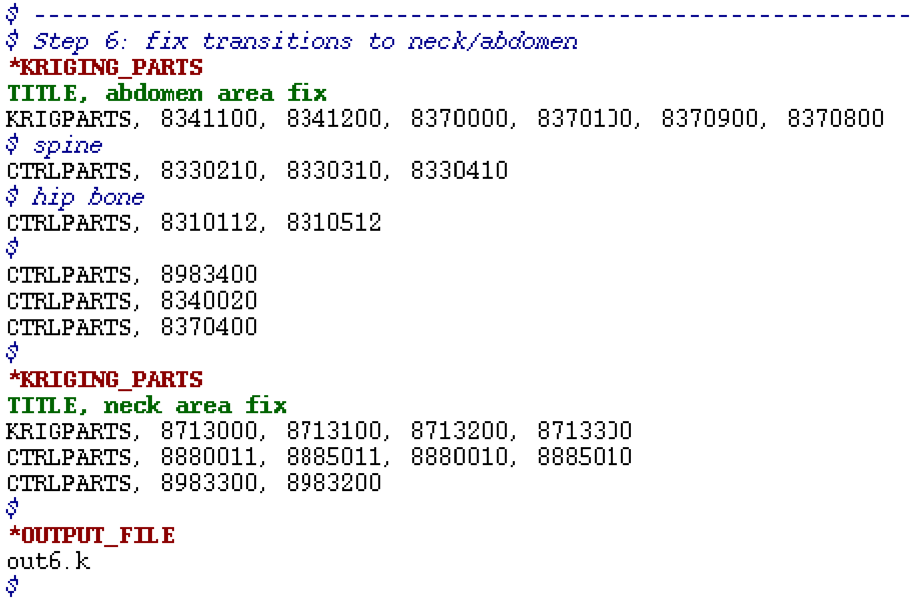
```
$ ------------------------------------------------------------
$ Step 5: fix skin/flesh
*KRIGING_PARTS
TITLE, fix skin/flesh parts
$ skin
KRIGPARTS,  8983000, 8983100, 8983200, 8983300, 8983400
$8370800,
$ outer costal pleura
KRIGPARTS, 8971000, 8971100
$ organs
KRIGPARTS, 8340020, 8940100, 8940200, 8950200
$ shoulder belt
KRIGPARTS, 8550100, 8550110, 8550500, 8550510
KRIGPARTS, 8650100, 8650110, 8650500, 8650510
$
$ rib base
CTRLPARTS, 8970200, 8970300, 8980200, 8971200, 8971300
$ inner costal pleura (Rippenfell)
CTRLPARTS, 8970000, 8970100
$
```

Multi-Step Thorax Interpolation

Step 6 – Adaptation of the transitions (neck/abdomen)

- given: costal pleura and thorax flesh
- kriging of neck and abdomen/pelvis parts





```
$ ----------------------------------------------------------------
$ Step 6: fix transitions to neck/abdomen
*KRIGING_PARTS
TITLE, abdomen area fix
KRIGPARTS, 8341100, 8341200, 8370000, 8370100, 8370900, 8370800
$ spine
CTRLPARTS, 8330210, 8330310, 8330410
$ hip bone
CTRLPARTS, 8310112, 8310512
$
CTRLPARTS, 8983400
CTRLPARTS, 8340020
CTRLPARTS, 8370400
$
*KRIGING_PARTS
TITLE, neck area fix
KRIGPARTS, 8713000, 8713100, 8713200, 8713300
CTRLPARTS, 8880011, 8885011, 8880010, 8885010
CTRLPARTS, 8983300, 8983200
$
*OUTPUT_FILE
out6.k
$
```

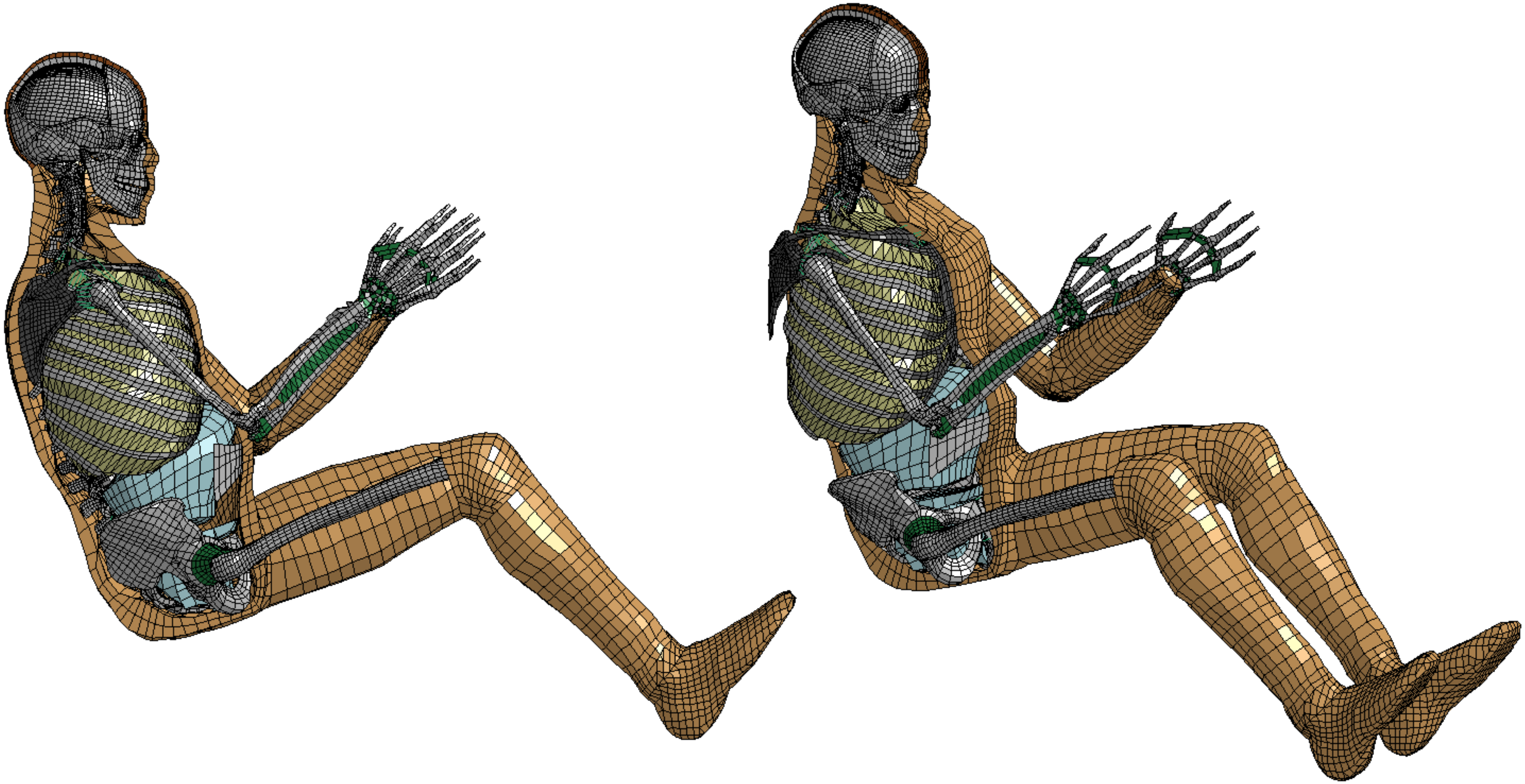
Summary

- ➢ steps 1-6 can be performed automatically
- ➢ variants possible by changing of parameters in input file
- ➢ model quality is very good

Multi-Step Thorax Interpolation

Step 7 – Model Fixes

- merge of new nodal coordinates into original model
- fix of extreme element distortions (only few in abdomen)
- fix of initial contact penetrations (only few)



Remarks & Outlook

Some Remarks

- dramatically risen interest in human body modelling in automotive industry
- currently frequent use of *old* THUMS V3.0 model
  - primary concern: model kinematics in various crash situations → THUMS4 too detailed (expensive)
  - THUMS 3 model is easier to handle (numerically and biomechanically, validation issue)
- THUMS V1-4 only passive models, THUMS V5 first active model → to be evaluated …
- no injury criteria yet available for THUMS model(s)
  - direct simulation of injuries desirable, but difficult to realize (injury mechanisms, model validation)
  - validation only w.r.t. crash situations, rather than biomechanical injury mechanisms

➢ *we are still at the beginning of human body modelling in automotive applications !!!*

Outlook

- increase validation database for all body regions
- increase biomechanical (user) knowledge required for result extraction
- first step: establishment of a THUMS Users Community (TUC)
  - join forces in THUMS development, gather biomechanical knowledge and develop/establish useable injury criteria
  - virtually all German automotive companies involved

  ➢ first project finished, follow-up project in preparation

The End …

Thank you for your Attention