Open access
virtual testing protocols
for enhanced
road user safety

Specification of OS-HBM data structures published on OpenVT platform and conference publications

WP number: 2
Deliverable: D2.1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 768960.

Specification of OS-HBM data structures published on OpenVT platform and conference publications

Work package 2, Deliverable D2.1

Please refer to this report as follows:
Iraeus, J., John, J., Svensson, M., Klug, C., Erlinger, N., Krašna, S. (2019). Specification of OS-HBM data structures published on OpenVT platform and conference publications, Deliverable D2.1 of the H2020 project VIRTUAL.

Project details:	
Project start date: Duration: Project name:	01/06/2018 48 months Open access virtual testing protocols for enhanced road user safety - VIRTUAL
Coordinator:	Astrid Linder, Adj Prof, PhD – Research Director Traffic Safety Swedish National Road and Transport Research Institute (VTI) Regnbågsgatan 1, 417 55 Lindholmen, Göteborg, Sweden
	This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 768960.

Deliverable details:	
Version: Dissemination level: Due date: Submission date: Online location:	Final CO (Confidential) 28/02/2019 28/02/2019 VIRTUAL Webforum Delievarbles

Lead contractor for this deliverable:
Mats Svensson – Chalmers

Report Author(s):	Iraeus, J., John, J., Svensson, M. (Chalmers), Sweden Klug, C., Erlinger, N., (TU Graz), Austria Krašna, S. (UL), Slovenia

Revision history

Date	Version	Reviewer	Description
	Preliminary draft 1	Jimmy Forsberg (DynaMore)	Review round 1 - Rating
	Final draft #	Names of Task leader: Mats Svensson (Chalmers) WP leader: Mats Svensson (Chalmers) QM, Coordinator	
	Final report	Name of English language reviewer: NA	
28 Feb 2019	Final deliverable	Astrid Linder – VTI ➔ EC	

Table of contents

Executive summary

As road users come in different sizes, ages, and genders WP2 will create the human body models (HBM) of both average female and male used in the VIRTUAL project activities in WP3,4 and 5 that can be scaled to represent these differnces. Specifically, WP2 will provide a set of HBMs ready for implementation in specified demonstration cases for seated occupants, Vulnerable Road Users (VRUs) and erect passengers in public transport. WP2 will exploit existing HBMs and supporting software previously developed in the national (VIVA) and the EU-funded (PIPER) projects. These open source resources will be further enhanced to extend their application and availability to the community.

The current document reports the results of **Task 2.1: "Modelling data structures and scaling strategies".** An initial planning phase for the OS models was performed to establish the processes and structures of the modelling activities.

Lessons learned from previous HBM activities were reviewed with Associated Partners and the Advisory Group. A workshop on Open Source Human Body Model Development was organised on October 17th, 2018 in Berlin. In order to maximise the attendance of highly experienced HBM experts, the workshop was held in conjunction with the Human Modelling and Simulation conference, October 18-19 in Berlin

For consistent application in the project, data file structures for the description of geometry, material properties, Injury Detection Systems (IDSs), and similar supporting input/output formats have been established. The developed data structures follow existing best practice, and have been openly documented for future development, potentially for regulation and standardisation procedures.

Scaling methodologies, to facilitate morphing the models for stature and age, were reviewed to identify important key issues to be considered in further model development.

The original reference models (PIPER child and VIVA OS-HBM 50F) have been configured and archived for traceability. The contents of this deliverable report will be used as input in VIRTUAL project publications.

1 Workshop on experience from previous HBM activities

This chapter is a synthesis of the experience of VIRTUAL partners and other international experts in HBM development and utilisation, summarised in the minutes of the VIRTUAL WP2 Workshop: Open Source Human Body Model development, Berlin - 17 October 2018. This result was initially reported in the VIRTUAL Milestone 2.1 document (Keller et al, 2018).

This workshop was organized to gather experts from industry, academia, and other organizations to discuss the current state of the art in development and use of computational human body model (HBM). The topics of discussion were selected by the partners in VIRTUAL WP2, and the output of the workshop has been used to refine the model development strategy of VIRTUAL including the data file structure and the scaling methodologies that are reported in chapters 2 and 3 in this document.

Speakers were invited to share their view, knowledge and experience on topics relevant to the overall objective of VIRTUAL. Each speaker presented a few slides to trigger questions and discussion with the attendees and project partners.

The VIRTUAL workshop was organised in conjunction with the CARHS 7th International Symposium on "Human Modelling and Simulation in Automotive Engineering" taking place in Berlin on 18 and 19 October. Five external experts were invited to give a short presentation on their experience on a selected subtopic.

Philippe Petit (Renault) gave some very important insights on HBM-scaling as well as on Open Source (OS) dissemination. A vital takeaway message was to ensure that we communicate with, and involve the PIPER consortium to ensure that we get the best out of the models and tools that are available and at the same time contribute to the Piper Community and do our best to avoid so called "forking" of the OS tools.

Duane Cronin (University of Waterloo) gave us valuable insights and elaborated on various forms of modularity that have been used. One takeaway message was that the type of modularity must be chosen based on the purpose of the given model or the given simulation case.

Steffen Peldschus (University of Munich/LMU) gave a presentation on Harmonised Objective Validation of human body models. The THUMS users community makes validation data available for a set of different load cases.

John Combest presented his view on Complex versus Simple HBMs, as well as a range of additional input, based on the experience in the GHBMC consortium. The GHBMC approach was to start from a detailed HBM and then also develop a simplified version where the occupant kinematics was in more focus. Future use of HBMs may vary over time. A new trend is the interest in novel seating positions and postures that may come as a result of vehicle automation.

Hyung Yun Choi shared his experience on translation of HBMs between different codes. One of his conclusions was that, if you want to develop an HBM that is prepared for translation into other codes, your model should be based on features that are common for the different codes.

In the final discussion we received a range of valuable advice and comments. University representatives were very grateful for our open source approach that provides them with easily accessible models that can be used in student projects.

Mats Svensson (Professor at Chalmers University of Technology), moderator of the workshop, gave an overview of the VIRTUAL project and presented the challenges we face today. Mats pointed out that the overall goal of the VIRTUAL project is to investigate the feasibility of virtual test procedures complementary to physical testing. VIRTUAL has picked a few well confined use cases, for instance whiplash injury, and it is only in those few cases that the biofidelity and injury assessment capability of the VIVA-HBM (addressing gender diversity) will be given priority.

1.1 Welcome and introduction

Mats Svensson (WP2 leader): General welcome to participants

- Motivation for workshop
- General presentation of **VIRTUAL**, see slides
- It was highlighted that VIRTUAL aims to establish a dialogue with other HBM related initiatives to ensure win-win collaborations

Johan Iraeus: Introduction to questions which should be addressed in this workshop (see slides)

- Possible approach to model refinement: Existing model → refine model and add injury detection systems → additional validations → morphing → re-position for test cases
- Or, different approach: Create “core model” → optimized morphing procedure → validation of morphed versions
- **Challenges:**
  - Morphing/scaling
  - Modularity
  - Simple vs. complex models
  - Validation of morphed? Modified? HBMs
  - Expected future use
  - Translation to other codes
  - Open Source (OS) issues/maintenance

Comments from the audience:

- Kinematic validation of the model might not be sufficient for use in product development as injury risk values are what will guide design decisions. What injury criteria will be used as result from HBM simulations?
- What is the age of the VIVA model today? What is the age of the individual that was used to derive the geometry and what age do the material parameters correspond to? There are several anatomical variations resulting from aging that perhaps need to be accounted for. Johan commented that the variation due to aging can be less than the variations observed within the human population
- Will you aim at simulating the full pre-crash sequence for pedestrians and bicyclists? Will the models include active muscles? Focus in project right now is to include active muscles to assess their

contribution to the response of the human body during the crash-phase and to the control of the posture during the pre-crash phase.

1.2 Invited speakers

Philippe Petit: Piper experience on scaling

- About PIPER: OS project, that provides a set of tools for positioning/personalisation that is independent of the FE solver used to run the simulation (should it be LS-DYNA, VPS, Radioss,…).
- The PIPER software uses a set of meta-data to manipulate any HBM, such as landmarks of certain bones etc. based on databases of anatomical landmarks.
- About developing a **core model:** there should be an **initial purpose** for the development of such a model. There is a trade-off between the ability to modify the model by morphing it and the level of details in the model. One needs to make the right choices to get a model that meets the desired requirements.
- Suggestion: "Go deep into PIPER" → Invitation to fill the open gaps and to contribute. Scripting in PIPER can be very useful for the core model approach.
- Request to VIRTUAL members to document, whenever something useful is identified or something is changed and to share experience with other PIPER users. Documentation of PIPER functions is currently incomplete.
- Validation of **morphable** core model: no experience with that, but it is probably difficult. A qualitative comparison of the GHBMC model to PMHS tests was presented by Philippe Beillas at IRCOBI this year (2018). However, it is not clear how morphing affects validation.

Duane Cronin: Modularity

- **Evolution of models:** Level of detail has mostly been given by what was computationally feasible and therefore significantly increased throughout the last years.
- Prediction of injury risk. It can be done based on different scales: Global (vehicle acceleration), Global biological response (multi-body model, dummy like criteria), local biological response (Injury risk at the tissue level).
- Modularity in the form of **substructuring** has been around in FE modelling since the 1970s.
- Another type of modularity: multi-scale modelling, using the results of a simulation of coarser model as boundary conditions for a more detailed model. Example: Model of blast exposure, simple whole body kinematics, more detailed head.
- Simplified components can work as long as St. Venant's criterion is met and the kinematics is correct. Example: side-impact with detailed thorax and simplified arms and head.
- A modular type of model "can work, if you ask the right questions."
- **Critical points:**
    - Simplified models have to be validated against full-complexity model
    - Transitions and boundaries where simplified and more complex structures are combined
    - Tissue level response is very sensitive to small changes in geometry

- **Questions/Comments from the audience:**
    - So many different models for different things – from an industrial perspective, it is sometimes better to only run **one** complex model of entire body. When you have to run multiple simulations with modular models instead of one simulation with a complex model, efficiency is limited and it is not beneficial from practical point of view, as not only one number is needed from one simulation.

- Modularity is not limited to the spatial domain, but also in the temporal domain which could further benefit from a modular approach. We also have to handle the age of the occupants which affects not only the anatomy but also material properties.
- It is hard to define a “normal” response to validate these models with. Natural variations in human population should not be ignored, but be taken into account (example of gait styles was given). Variability in terms of geometry and material properties is increasing with age. The validation with PHMS tests became more difficult over time because of increasing average age of body donors.
- Aging is not only a morphing exercise, tissue level changes make it very challenging
- The purpose and limitations of the model have to be clearly defined. We are currently often facing the challenge that we try to answer bigger questions than we had in mind when developing today’s state-of-the art models.
- It is recommended to start with a detailed model as core model and then simplify specific body regions depending on the intended application
- Suggestion to use a “population” of HBMs to deal with inter-individual variability. That would be easier to do with simplified/modular models.
- One way forward for more detailed validation could be the use of open source models, because then more efforts can be put into validation and development of models to capture more detailed responses.
- How much computational time does sub structuring save? → Answers from “5-10%” up to “8 to 10 times.” But: Trade-off between time gain in running the models and time invested for developing/validating reliable simplified models.
- Benefit of modularity and simplified models is highly dependent on the characteristic time of the event of interest. For instance, running pre-crash and in-crash simulations can take months with a detailed model.
- Assessment with tissue-based criteria can be challenging as pre-stresses from repositioning need to be considered.

Steffen Peldschus / Therese Fuchs: Harmonised Objective Validation

- Working on a set of **validation load cases** made available on web page of THUMS user community (TUC) in validation repository.
- A limitation in their work is that they cannot publish any details of the HBM, as all details of THUMS are IP protected. Therefore very detailed documentation is needed to specify the setup of the validation tests in a generic way. There will be an advantage in using Open Source models for the harmonisation of validation activities, as it will be possible to include the HBM in the setup files.
- Already available load cases:
    - Rib bending tests, lateral loading (Del Pozo et al. 2011)
    - Pedestrian load case with beta model of the SAE pedestrian impact buck (PMHS tests published by Forman et al., 2015)
- Load cases in preparation:
    - Load cases from SENIORS project. Tests were done with both volunteers and PMHS. TUC processes the data and generates FE environment for simulation of the tests. Subsystem (femur, intervertebral disc tests) setups on being prepared
    - Frontal sled tests (Gold standard) from Shaw et al. (2009)
    - Femur tests published by Forman at el. (2012)
    - Disk compression (lumbar spine) – validation presented at IRCOBI this year by Draper et al
- TUC is open for collaboration with other initiatives

- **Questions/comments from the audience:**
    - European Commission funding rule: data produced by funded projects must be made available, even if it has not been exploited within the project. Therefore, it is likely that there is more “hidden” data around which could be published in a similar fashion. During PIPER project, it was sometimes difficult to obtain this kind of data from other research groups (in spite of EC requirements)
    - OS HBMs should be beneficial, as the HBM as a whole could serve as “information container” (e.g. for CT data on subject size or initial posture of the PMHS)

John Combest: Complex vs. Simple HBMs, GHBMC experience

- John Combest works at Nissan and is the chairman of the GHBMC.
- It is good to see discussions and groups promoting use cases for HBMs.
- GHBMC used **different approach**: detailed → simple. They started with detailed models of single individuals, representative of the average morphology. At a later stage, simplified models were derived from complex models.
- Concerning the issue of “**future use:”** Number one goal for GHBMC is to provide a model **for a specific purpose**: Focus is on accurate modelling of crash induced injuries. GHBMC is very focused (no models of bicyclist, motorcyclists, modelling of sport injuries,.).
- Open Source approach: That is a novelty from the industrial perspective. A challenge for the open source models if their long-term maintenance.
- Validation: Sometimes, experiments are hard to reproduce due to missing detailed information about experimental setup. GHBMC used the validation load cases that were reproducible.
- Regarding to modularity, it is challenging to decide where to section the model. Perhaps the spine is more of a functional unit than the thorax for instance. Modularity was not considered by GHBMC.
- What applications the model will be used for is difficult to anticipate – novel developments right now are relaxed reclined positions.
- Industry is also interested in ATD-like HBMs.
- “Morphing for age is more challenging than morphing for size.”
- “All models are wrong – just some are useful.”
- It is essential to decide how the models should be used.

Hyung Yun Choi: Multiple Codes and Translation

- Quick survey of the solver use in the audience: 1. LS-DYNA (approx. ~70%), 2. VPS (~20%), and 3. Radioss and 3. Abaqus (~5% or so each, tie).
- **Model conversion process:** LS-DYNA input model→converted to VPS or RADIOSS → validation→ release.
- Validation: a number of **defined load cases** at multiple length scales (components, upper body, full body). Translated models are correlated with PMHS data. This can be problematic when the translated models perform better than the original ones, which can lead to inconsistencies among the models in different codes.
- About **core model:** should use features which exist in all codes and are therefore easy to translate.
- Upcoming developments for the GHBMC: an active model which will be validated w.r.t. data from Beeman et al.

- **Questions/comments from the audience:**
  - There is a paper by Therese Fuchs on model translation
  - Input from translation point of view to GHBMC is to only use features which work across multiple FE solvers. There are a lot of features in LS-DYNA which do not exist in VPS or Radioss
  - Benchmark for element definitions, plastic strain definitions, contact definitions in different FE solvers would be useful

1.3 Discussion and questions

Question by P. Petit: Why are we talking so much about models and not about test protocols?
Mats Svensson's answer: In VIRTUAL, a few uses cases will be targeted for virtual testing. One of the use cases is rear end collision with a focus on whiplash injuries. The VIVA model, which is the starting point for the VIRTUAL models, is developed particularly for this purpose. Criteria we will look at in the VIVA model is facet ligament strain and spinal fluid pressure transients. When it comes to whiplash protection systems, we will then use the models to extend the test results. Parameters to change are for instance the sex and size of the occupant. It is possible that this will show a need for adaptivity in protective systems in vehicles.

Mats Svensson: Quick summary of the discussion so far. Are there other comments or questions?

Comments from the audience:
Answer from VIRTUAL partners (if any) are shown in Italic.

- For universities, Open Source models are very helpful. However, using coherent terminology would be very helpful. Therefore, common name spaces, standards for development procedures etc. should be specified. PIPER is probably a good standard for that.
- Which unit system is being used, and how can different unit systems be translated?
  *A: mm ms kg is used in VIVA. *INCLUDE_TRANSFORM should work for most situations.*
  The effect of unit translation on strain rate parameters should be checked. Include files in different unit systems might be useful.
- Morphing is challenging and risks producing bad outputs. Going from seated occupant to standing model will most likely require manual remeshing.
- Is there a demonstrator for simplified/modular models?
  A: For the VIVA model currently most body regions are simplified, as focus was put on the neck.
- For pre-crash simulation it would be more interesting to have a simplified model with active muscle control, as detailed models need much computational time for this long time frames.
- Are you using PIPER or implicit calculations for positioning?
  A: We intend to use PIPER for positioning. Positioning can be done there either geometrically or through a script so that positioning is performed during pre-simulations.
- An interesting offer would be seminars and /or tutorials. That might help with long-term sustainability.
  A: Dynamore will take care of such activities and is an important partner for VIRTUAL to ensure sustainability.
- Which injury scale is used, and how is injury linked to strain?
  A: Defining proper criteria is challenging for some body parts. We aim to have Injury Detection Systems implemented in the HBMs that are able to predict injury of specific AIS severity.

2 Data File Structures

This chapter describes data file structures of the models that will be developed in the VIRTUAL project. The data file structure, which primarily comprises of the include file structure and identifier numbering system, was designed to facilitate collaborative and open research, modular utilization of the models and future development.

The data file structure definition mainly focused on numbering convention for parts, materials, and other properties of the model components, include file structure and techniques for assembling the submodels into a full Human Body Model (HBM).

2.1 Identifier Numbering System

The numbering system for the VIRTUAL human body model components consists of a 7-digit identifier. Components/organs are identified with the first 6 digits and 7th digit is used for material model/property definitions. The description of part, section and material numbering in this section is described based on the LS-DYNA keyword structure, as this will be the primary FE solver used in the VIRTUAL project.

A part representing the component/organ and the section definition of the respective part will have the same identifier. Moving from left to right of the identifier locates the component with increasing level of detail (Figure 2-1). The hierarchy of detail follows the order: Body region, sagittal aspect (left/right), component/organ within the body region, sub-components (to be used if detailed geometric and material definitions are required for a component). The last digit will be 0 by default for part/section numbers, as this digit is used for material property definition.

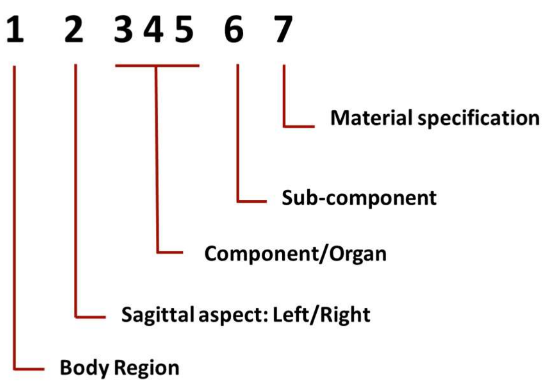

Figure 2-1: Numbering system for components of the VIRTUAL human body model.

The material ID will share the same initial six digits as that of the part to which it is assigned. The 7th digit of the identifier will be used to include predefined material definitions in the keyword files for easy toggling between material types as required by the simulation load case and study objectives. The same numbering system will be used in the definition of property curves and tables

The numbering convention for each level of hierarchy is described below with examples.

2.1.1 Body Region

The first digit in the identifier is used to specify the general body region of the model. The description of body regions and abbreviation for part naming is given in Table 2-1.

Table 2-1: The first digit in the identifier describes the general body region.

Body region number	Description	Abbreviation
1 X XXX X X	Head	HE
2 X XXX X X	Neck	NE
3 X XXX X X	Thorax	TX
4 X XXX X X	Abdomen	AB
5 X XXX X X	Pelvis	PE
6 X XXX X X	Upper Extremity	UX
7 X XXX X X	Lower Extremity	LX
9 X XXX X X	General (Miscellaneous)	MI

2.1.2 Sagittal Aspect (Left/Right side of the body)

The position of the entity with respect to the mid-sagittal plane, i.e. left or right side of body, is described by the second digit of the identifier. This is given to utilize the symmetric nature of the human body for an efficient and logical numbering scheme. The left and right extremities follow the same numbering scheme, rather than separate body region identifier. Hence, symmetric components will have identifiers that are offset by 500,000. Node numbering will also follow the same number scheme as the body region and sagittal aspect.

Table 2-2: Second digit describes the sagittal aspect of the component

Sagittal Aspect	Description	Abbreviation
X 0 XXX X X	Left	L
X 5 XXX X X	Right	R

This numbering scheme will also facilitate easier post-processing of tissue responses on the two sides of the mid-sagittal plane. For example, left and right capsular ligaments of the spinal column, which respond differently for all loading except in pure forward or rear-ward impacts. Components located on the mid-sagittal plane will have a default value of 0, unless further sub-division is required for the sake of post-processing. For instance, separate output for responses of right and left halves of the intervertebral disc or spinal ligaments may of be interest in side/oblique impact, in which case, the components can be defined as different parts using this numbering system.

2.1.3 Component/Organ

The third to fifth digits of the identifier is used to describe components/organs in respective body regions. The identifiers used in the detailed model will be updated on the OpenVT platform wiki as the model development progresses. General rules for consistent numbering and logical progression are given below with examples.

The component identifier for a given body region is numbered in increasing order from superior to inferior direction. In the presence of multiple components at the same level, the components are numbered from the medial to lateral direction in the supine position, for example, ulna and radius. An example of the right upper extremity skeletal system is given in Table 2-3.

Table 2-3: An example of component identifier numbering in the upper extremity skeletal system

Component Identifier	Description
65 001 XX	Humerus
65 002 XX	Ulna
65 003 XX	Radius
65 004 XX – 65 011 XX	Carpal Bones
65 012 XX – 65 016 XX	Metacarpal Bones
65 017 XX – 65 030 XX	Phalanges

The third digit serves as a general identification for hard and soft tissue, and joint definitions. The ranges given in Table 2-4 are recommended.

Table 2-4: Ranges of component identifier for hard and soft tissues

Component Identifier	Description
XX 0XX XX – XX 2XX XX	Skeletal components (Bones and cartilages)
XX 3XX XX – XX 8XX XX	Soft tissues (Ligaments, Muscles, Skin, etc)
XX 9XX XX	Simplified joint definitions

In the presence of repeating structural units in a body region, consecutive numbers will be assigned to the repeating units. Components of spinal column (vertebrae, intervertebral disc, spinal ligaments and muscles) and ribs are few examples were this numbering rule is applicable. An example of the numbering of components in the thorax is in Table 2-5.

Table 2-5: Numbering of repeating structures in a body region, shown with an example of thorax

Component Identifier	Description
3 X 001 XX – 3 X 012 XX	Thoracic vertebrae (T1-T12)
3 X 101 XX – 3 X 112 XX	Ribs
3 X 301 XX – 3 X 312 XX	Intervertebral discs (Thoracic spine)
3 X 321 XX – 3 X 332 XX	Anterior Longitudinal Ligaments (Thoracic Spine)
3 X 341 XX – 3 X 342 XX	Posterior Longitudinal Ligaments (Thoracic Spine)

3 X 351 XX – 3 X 362 XX	Capsular Ligaments (Thoracic Spine)
3 X 371 XX – 3 X 382 XX	Ligamentum Flavum (Thoracic Spine)
3 X 391 XX – 3 X 402 XX	Interspinous Ligament (Thoracic Spine)
3 X 411 XX – 3 X 421 XX	Intercostal muscles
3 X 500 XX	Thoracic cavity
3 X 901 XX – 3 X 912 XX	Thoracic intervertebral joints (for simplified model)

2.1.4 Sub-component

Many structural components of the human body consist of multiple types of tissues. For example, bones (trabecular and cortical structures) or intervertebral disc (annulus and nucleus). The sixth digit in the identifier can be utilized for this purpose. The provision for a sub-component is provided to easily add detail in a component under the same component identifier. This identifier is dependent on the requirements of a given component and the model developer assigns the 6th digit in the identifier as required. An example of C6-C7 cervical spine motion segment and left femur bone is given in Table 2-6.

Table 2-6: Numbering of subcomponent. An example of C6-C7 cervical spine motion segment

Component Identifier	Description
2 0 006 1 X	C6 Cortical
2 0 007 1 X	C7 Cortical
2 0 006 2 X	C6 Trabecular
2 0 007 2 X	C7 Trabecular
2 0 306 1 X	C6-C7 Annulus Ground
2 0 306 2 X	C6-C7 Nucleus Pulposus
2 0 306 3 X – 2 0 306 9 X	C6-C7 Annulus Fibres
7 0 001 1 X	Left Femur Cortical
7 0 001 2 X	Left Femur Trabecular

2.1.5 Material specification

The seventh digit of the identifier is primarily used with the material cards to pre-define material definitions for easy toggling between material definitions/models as required by a load case or study objective. Hence, this digit is assigned 0 for part and section identifier. However, if null element definition is required for a component, then the identifier for the null element part/section can be defined with 9 in the seventh digit. For example, X X XXX X 9.

In the material card, the value 0 for the seventh digit in the identifier will be reserved for rigid material definition. The rest of the numbers can be utilized for pre-defined or user-defined material definitions (Table 2-7). The pre-defined material models will be evaluated for their behaviour in the VIRTUAL models before inclusion in the model keyword deck.

Table 2-7: Numbering of seventh digit in the identifier for material definition

Component Identifier	Description
X X XXX X 0	Rigid Material
X X XXX X 1 - X X XXX X 9	Pre-defined/User-defined Material Models

2.2 Include file structure

Along with identifier numbering system, the VIRTUAL include file structuring intends to exploit the flexibility in the LS-DYNA keyword structure and include file possibilities to develop an efficient modelling framework that aids modularity, collaborative model development and integration. The include file structure shown in Figure 2-2 is proposed to be used in VIRTUAL models. Each body region will be defined as a separate include file directory. The integration of the body regions as a single model will be realized through a model integration include file.

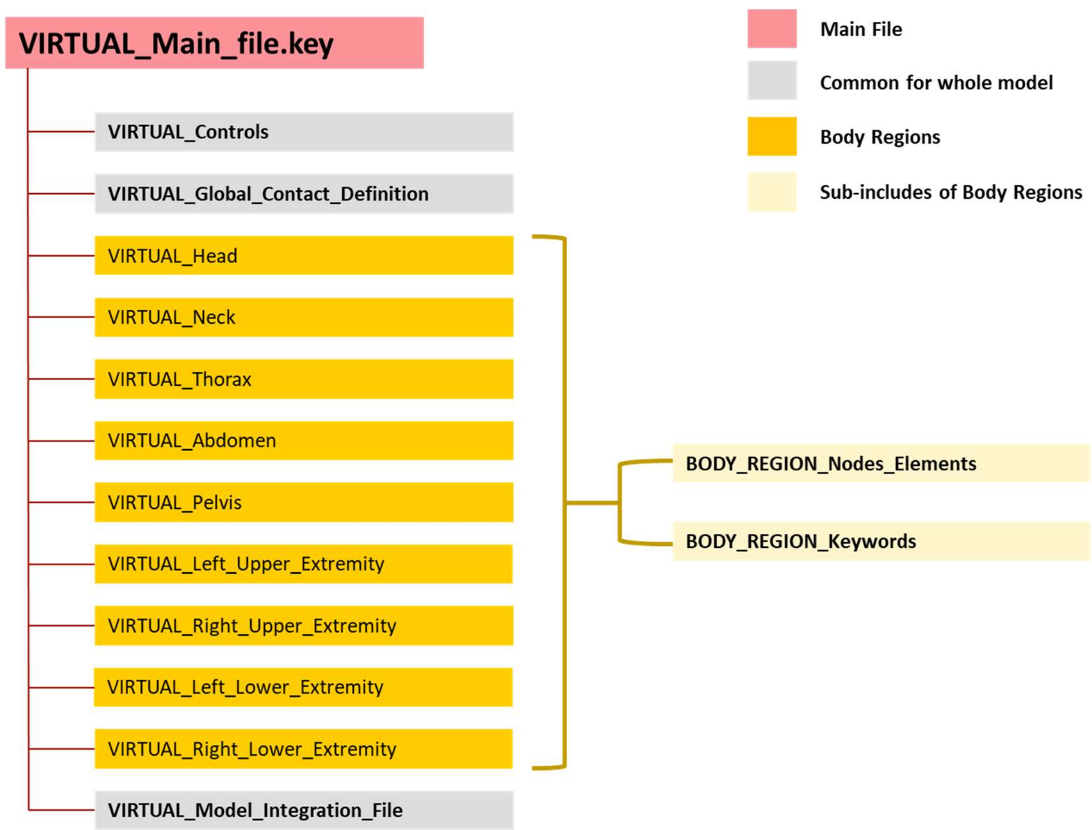

Figure 2-2: VIRTUAL include File structure

Each body region is divided into two sub-include files—one file consisting of the node and element defintions and another file consisting of the rest of keywords associated with model defintions. This structure will be advantageous for effortless mesh modifications, both during development and later for applications using mesh morphing. With this include file structure for the body regions, only the 'nodes and elements' include file need to be replaced after mesh changes, for example, during mesh refinement or posture changes.

In addition to the general include file structure shown in Figure 2-2, VIRTUAL partners may also implement further modularity during the development stage — with further include file sub-structuring based on components, geometry, materials, etc. This will facilitate straightforward isolation of parts for component-wise validation. An example of such an include file sub-structuring method is shown in Figure 2-3. The include files thus generated during sub-structuring for the development process will be merged in the end to obtain the VIRTUAL include file structure shown in Figure 2-2. However, such files generated during the development process will be made available on the OpenVT platform as 'developer' version to enable faster model changes and assessments for future development.

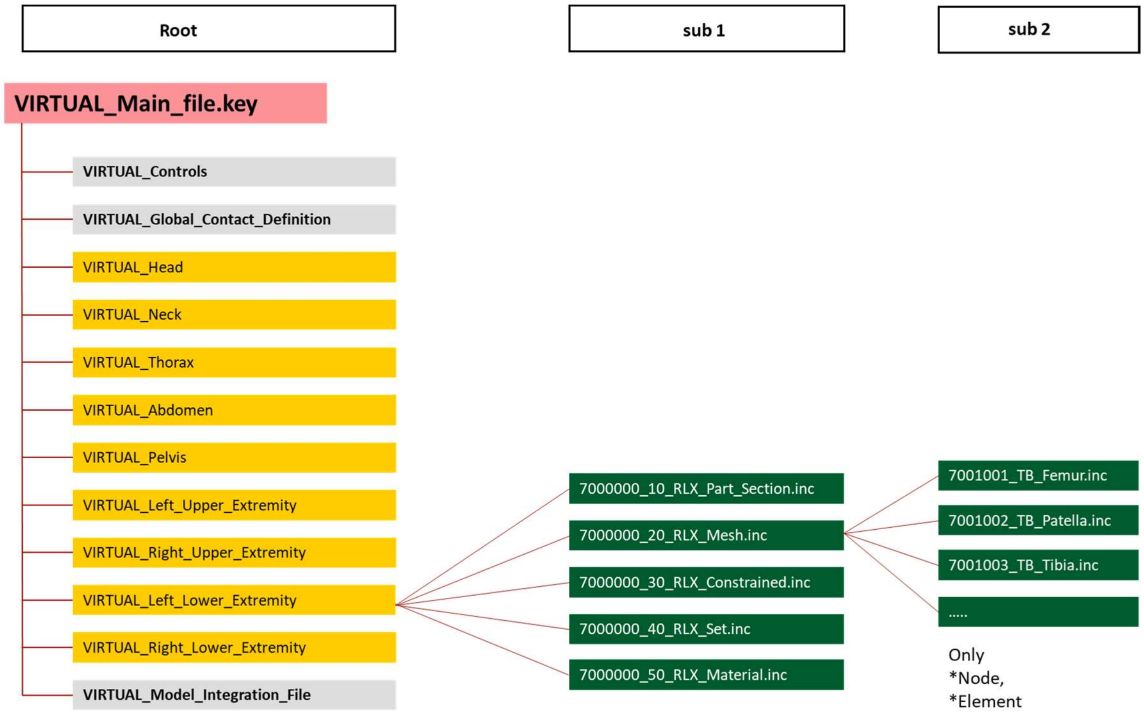

Figure 2-3: An illustration of the include file sub-structuring during the model-development stage

3 Scaling Methodologies

The different models to be used in the VIRTUAL work packages will be generated from a baseline model. This chapter describes the work flow of the scaling methodologies that will be used to generate the various models.

The different models of occupants and road users that will be developed in the VIRTUAL project will be generated from an initial model of average female (ViVA F50), which will serve as the baseline model. Generating the different models from a single baseline model will allow for meaningful inter-model comparisons of responses. For the generation of these multiple models, FE mesh morphing tools will be extensively used, primarily the open-source PIPER library and routines available in commercial FE preprocessor ANSA (BETA CAE).

3.1 Development of the Average Female and Male models

The human body model of average female occupant, VIRTUAL F50, will be first developed based on the ViVA open source model. This model will serve as the baseline model for the different work packages in the VIRTUAL project. The average male occupant model, VIRTUAL M50, will be obtained by global morphing of the F50 model. Further, the spine alignment of M50 and F50 models will be positioned to represent the gender-dependent variations reported from recent studies (Sato, 2019; Sato et al., 2017). The road user models of pedestrians and cyclists for WP-4 and standing occupants for WP-5 will be generated from M50 and F50 models by positioning of the upper and lower extremities and spine alignment (Figure 3-1).

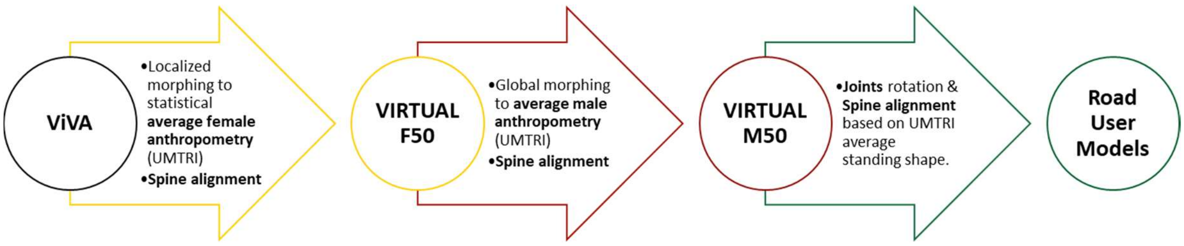

Figure 3-1: Overview of workflow for the generation of models to be used in the VIRTUAL project. The VIRTUAL F50 model, which will be developed from the ViVA model, will serve as the baseline model.

3.1.1 Anthropometry

The anthropometry of the average models will follow the same methodology as in recent human body models. Development of most crash test dummies (BioRID (Davidsson et al., 1998), WorldSID (Moss, Wang, Salloum, & Reed, 2000)) and simulation models (THUMS (Iwamoto et al., 2002), GHBMC (Gayzik et al., 2009), EvaRID (Carlsson et al., 2014)) were based on the detailed Anthropometry study of Motor Vehicle Occupants (AMVO) conducted at the University of Michigan in the early 1980s for the development of the average dummy (Schneider, Robbins, Pflug, & Snyder, 1983). Volunteers representing the average anthropometry in the AMVO study were selected based on the stature and BMI reported from the first National Health and Nutrition Examination Survey conducted in the United States between 1971 and 1974 (Abraham, Johnson, & Najjar, 1979). In addition to establishing the average anthropometry based on AMVO, many model development efforts verify the average body dimensions with the first Anthropometric Survey of U.S. Army Personnel (ANSUR I) (Gordon et al., 1988).

Although the current models are based on an anthropometric survey almost half-a-century old, Moss et al. (2000) noted that stature of these models is representative of the global vehicle occupant. Recent analyses of world-wide population-based studies, however, show an increasing trend of BMI. An analysis covering 19.2 million adult global population showed that age-standardized average BMI increased from 21.7 kg/m^2 in 1974 to 24.2 kg/m^2 in 2014 for men, and from 21.4 kg/m^2 in 1974 to 24.4 kg/m^2 in 2014 for women (NCD Risk Factor Collaboration (NCD-RisC), 2016), while the data for the EU show even larger BMI increase (Global Health Observatory Data Repository). This increase in body mass could result in variations in soft tissue geometry, for example, waist circumference (Moss et al., 2000). This can also be seen in the ANSUR II (2012) data, which shows an increasing trend for lateral body dimensions with increase in BMI (Figure 3-2). As this variation in body mass can be expected to influence the vehicle occupant responses and interaction with seat and restraint systems, it may be necessary to consider updated BMI for definition of the average models. The morphing methods to be used in VIRTUAL will enable future modifications of HBMs to consider trends in human body size in EU and world population.

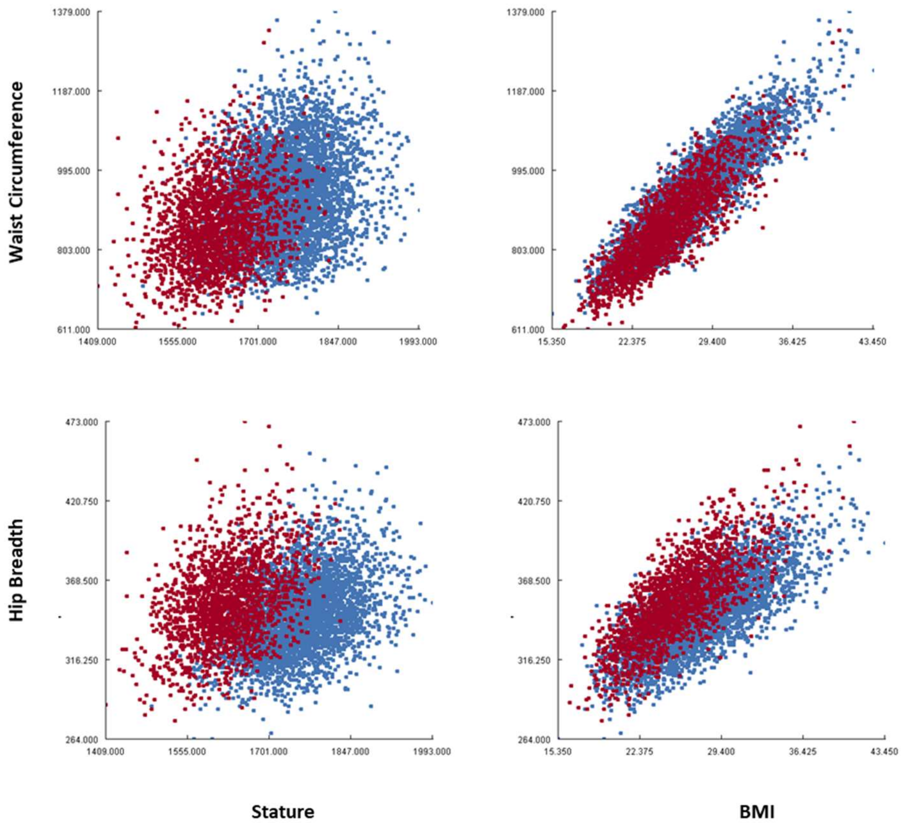

Figure 3-2: Waist circumference and hip breadth variation with respect to stature and BMI (ANSUR II, 2012). Red data points represent female and blue represents male.

3.1.2 VIRTUAL F50 Model

The VIRTUAL average female F50 occupant model will be based on the existing open source ViVA model (Östh, Mendoza-Vazquez, Linder, Svensson, & Brolin, 2017). The ViVa model currently consists of detailed neck definitions with a coarse definition for the rest of the body (which is currently used to act as a boundary condition for the detailed cervical spine). This model will be further developed to include updated definitions as per the requirements of WP-3, WP-4, WP-5. The VIRTUAL F50 will have updated body mass definitions to correspond to the global average weight and height, while retaining the current stature which is considered representative of average global occupant (Moss et al., 2000). In addition, the recline of the occupant model will be updated. For this purpose, the outer shape of the VIRTUAL F50, and skeletal and joint landmarks will be based on the statistical average shape generated from volunteer anthropometry studies conducted at University of Michigan Transportation Research Institute (UMTRI) (Park & Reed, 2016). The anthropometry of the model will also be verified with the recent Anthropometric Survey of U.S. Army Personnel (ANSUR II) using multi-variate regression based on stature, body mass, and gender (Gordon et al., 2012).

3.1.3 VIRTUAL M50 Model

The VIRTUAL average male M50 model will be generated from F50 model using global morphing, which will involve non-linear scaling and shape variations. The UMTRI average male shape corresponding to the global BMI will be used as the template for surface shape and skeletal landmark (Park & Reed, 2016). In addition, anthropometry of the model will be verified with the ANSUR II database, as performed for VIRTUAL F50.

The internal geometries of the skeletal structure will be modified to ensure that they correspond to the males. The cortical structure of the long bones will be updated based on the statistical average definitions (Klein, Hu, Reed, Hoff, & Rupp, 2015). The pelvis skeletal shape will be updated to reflect gender variations (Wang et al., 2004). The curvature of the spinal column will be updated to represent male average curvature, with a lordotic cervical column and more kyphotic thoracic column (Sato et al., 2017).

3.1.4 Road User Models

The VIRTUAL M50 and F50 occupant models will form the baseline model for the generation of pedestrian and cyclist road user models and standing occupant models in WP4-WP5. The first step will be to generate a standing model to correspond to the statistical average shape models of standing males and females (Park & Reed, 2016). This step will require repositioning of the upper and lower extremities, spinal alignment, and head to standardized positions (Klug & Ellway, 2018). The cyclist models will be further produced by the joint rotations of extremities to match different seated posture on bicycle (Klug, Feist, & Wimmer, 2018). The baseline VIRTUAL average models will be developed with high-quality mesh at the skeletal joints to minimize the need to remesh soft tissues after repositioning of joints.

References

Abraham, S., Johnson, C. L., & Najjar, M. F. (1979). *Weight and height of adults 18-74 years of age: United States, 1971-1974. Vital Health Statistics* (Vol. 11).

Carlsson, A., Chang, F., Lemmen, P., Kullgren, A., Schmitt, K. U., Linder, A., & Svensson, M. Y. (2014). Anthropometric Specifications, Development, and Evaluation of EvaRID-A 50th Percentile Female Rear Impact Finite Element Dummy Model. *Traffic Injury Prevention*, *15*(8), 855–865. https://doi.org/10.1080/15389588.2014.885647

Davidsson, J., Svensson, M. Y., Flogärd, A., Häland, Y., Jakobsson, L., Linder, A., … Wiklund, K. (1998). BioRID I - A New Biofidelic Rear Impact Dummy. In *IRCOBI Conference* (pp. 377–390). Gothenburg.

Gayzik, F. S., Hamilton, C. A., Tan, J. C., McNally, C., Duma, S. M., Klinich, K. D., & Stitzel, J. D. (2009). A Multi-Modality Image Data Collection Protocol for Full Body Finite Element Model Development. *SAE Technical Papers*, *4970*. https://doi.org/10.4271/2009-01-2261

Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., … Kristensen, S. (2012). *Anthropometric Survey Of U.S. Army Personnel: Methods And Summary Statistics*.

Gordon, C. C., Churchill, T., Clauser, C. E., Mcconville, J. T., Tebbetts, I., & Walker, R. A. (1988). *1988 Anthropometric Survey of U . S . Army Personnel : Methods and Summary Statistics*. *Security*.

Iwamoto, M., Kisanuki, Y., Watanabe, I., Furusu, K., Miki, K., & Hasegawa, J. (2002). Development of a finite element model of the total human model for safety (THUMS) and application to injury reconstruction. *Proceedings of the International Research Council on the Biomechanics of Injury Conference*, *30*, 12 p.

Keller, A., Östh, J., Klug, C. (2018) Open Source Human Body Model development - Minutes of meeting. Workshop: Berlin, October 17, 2018, https://projectvirtual.eu/wp-content/uploads/2018/11/minutes-VIRTUAL-Workshop-Berlin-October-17-2018-11-01-1.pdf
Berlin - 17 October, 2018

Klein, K. F., Hu, J., Reed, M. P., Hoff, C. N., & Rupp, J. D. (2015). Development and Validation of Statistical Models of Femur Geometry for Use with Parametric Finite Element Models. *Annals of Biomedical Engineering*, *43*(10), 2503–2514. https://doi.org/10.1007/s10439-015-1307-6

Klug, C., & Ellway, J. (2018). *Pedestrian Human Model Certification TB 024 v 1.1*. *EURO NCAP Technichal Bulletin*. Retrieved from www.euroncap.com

Klug, C., Feist, F., & Wimmer, P. (2018). Simulation of a Selected Real World Car to Bicyclist Accident using a Detailed Human Body Model. *IRCOBI Conference*, 182–183.

Moss, S., Wang, Z., Salloum, M., & Reed, M. (2000). Anthropometry for WorldSID A World-Harmonized Midsize Male Side Impact Crash Dummy. *SAE Paper*, (724). https://doi.org/2000-01-2202

NCD Risk Factor Collaboration (NCD-RisC). (2016). Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19·2 million participants. *Lancet (London, England)*, *387*(10026), 1377–1396. https://doi.org/10.1016/S0140-6736(16)30054-X

Östh, J., Mendoza-Vazquez, M., Linder, A., Svensson, M. Y., & Brolin, K. B. (2017). The VIVA OpenHBM Finite Element 50th Percentile Female Occupant Model: Whole Body Model Development and Kinematic Validation. In *IRCOBI Conference Proceedings* (pp. 443–466).

Park, B. D., & Reed, M. P. (2016). Human Shapes: Realistic Human Body Shape Modeler based on Real Data. Retrieved from http://humanshape.org/

Sato, F. (2019). *Does Spinal Alignment Influence Car Occupant Responses?* Chalmers University of Technology.

Sato, F., Odani, M., Miyazaki, Y., Yamazaki, K., Östh, J., & Svensson, M. (2017). Effects of whole spine alignment patterns on neck responses in rear end impact. *Traffic Injury Prevention*, *18*(2), 199–206. https://doi.org/10.1080/15389588.2016.1227072

Schneider, L. W., Robbins, D. H., Pflug, M. A., & Snyder, R. G. (1983). *Development of Anthropometrically-based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Volume 1*.

Wang, S. C., Brede, C., Lange, D., Poster, C. S., Lange, A. W., Kohoyda-Inglis, C., … Garton, H. J. (2004). Gender differences in hip anatomy: possible implications for injury tolerance in frontal collisions. In *Annual proceedings. Association for the Advancement of Automotive Medicine* (Vol. 48, pp. 287–301). Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15319131%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3217425