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# PIPER Final publishable summary

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**Table of content**

# 1. Executive summary

In passive automotive safety, advanced Human Body Models for injury prediction based on the Finite Element (FE) method (e.g. Thums or GHBMC families) have the potential to represent the population variability and to provide more accurate injury predictions than alternatives using global injury criteria. However, these advanced HBMs are underutilised in industrial R&D. Possible reasons include difficulties to position the models – which are typically only available in one posture – in actual vehicle environments, and the limited representation of the population variability (size, weight, limited availability for specific populations such as children, etc.). As the models and methodologies to use them are not standardized or widely shared, research achievements have been slow to result into safety benefits for the whole community.

The main objective of the PIPER project was to develop user friendly tools to position and personalize these advanced HBMs, and to share them widely with the community. By facilitating the generation of population and subject-specific HBMs and their usage in production environments, the PIPER tools will enable new industrial R&D applications for the design of restraint systems as well as in research.

After a specification phase to which the community could participate, the project developed an Open Source software framework to facilitate the positioning and personalizing of human body models for safety. The framework can be used with the leading HBMs and, because of its modularity, it could be further extended by users. It already provides many modules developed by the partners including state of the art real time simulation techniques for positioning, advanced morphing techniques to match various population dimensions, or smoothing approaches. The project also developed a new Open Source child model which can be used to describe children of age between 1.5 and 6 years during impacts and interactions with child restraint systems. The model performance has been extensively checked against and the model has its own dedicated module in the PIPER framework to facilitate the age change. Other project results included the development of generic car environments to facilitate comparisons and future work on accident reconstructions, and various software tools and geometrical datasets.

A first evaluation was performed within the project through a few crash applications that were selected for their safety relevance. Performed by both industrial and academic partners, these included among others pedestrian to generic vehicle impact, postural changes due emergency manoeuvres (pre-crash) followed by a crash and child accident reconstructions. Scaling and/or positioning were performed in each application and adult models from the GHBMC and Thums families were used besides the PIPER child model. The results demonstrated the usability and the potential of the software and child model. Most results were documented in tutorials for future users.

After selecting open source licenses, the PIPER framework and child model were first released at the final workshop of the project on April 25, 2017. Numerous academic and industrial users had already raised their interest during the project and provided useful inputs at various dissemination events and the workshop was well attended by both industry and academia. The initiation of an Open source project (www.piper-project.org) to continue promote the PIPER's vision and results beyond the end of the EU project was also announced at the workshop. Links to the project results, documentation, and other information can be found on the Open Source project Website.

# 2. Summary description of project context and objectives

## *2.1 Context*

In passive road safety, human variability is currently difficult to account for using crash test dummies and regulatory procedures. However, vulnerable populations such as children and elderly need to be considered in the design of safety systems in order to further reduce the fatalities by protecting all users and not only the so called average users. Also, new trends in vehicle automation may lead to new situations during the pre-crash phase (emergency manoeuvres) or new occupants postures that would be difficult to address with the current dummies.

Advanced Human Body Models (HBM) for injury prediction based on the Finite Element (FE) methods have the potential to represent the human variability and the diversity of postures. They can provide information that is complementary to what can be predicted with dummies or multi-body human models. Dummies and multi-body body human models are simplified human representations that can mostly predict a global kinematic response and global injury criteria. Because FE models include descriptions of anatomical components with their material properties, they are potentially capable of predicting complex deformations patterns when subjected to loading during impact events, including strain and stress in tissues that can be correlated with injury risks to specific structures. These advanced HBM have been continuously improving for the past 15 years, leading to recent models such as the THUMS or the GHBMC models (Figure 1) which are able to simulate the global response of the full human body in a variety of impact strenuous conditions while providing a number of injury predictors.

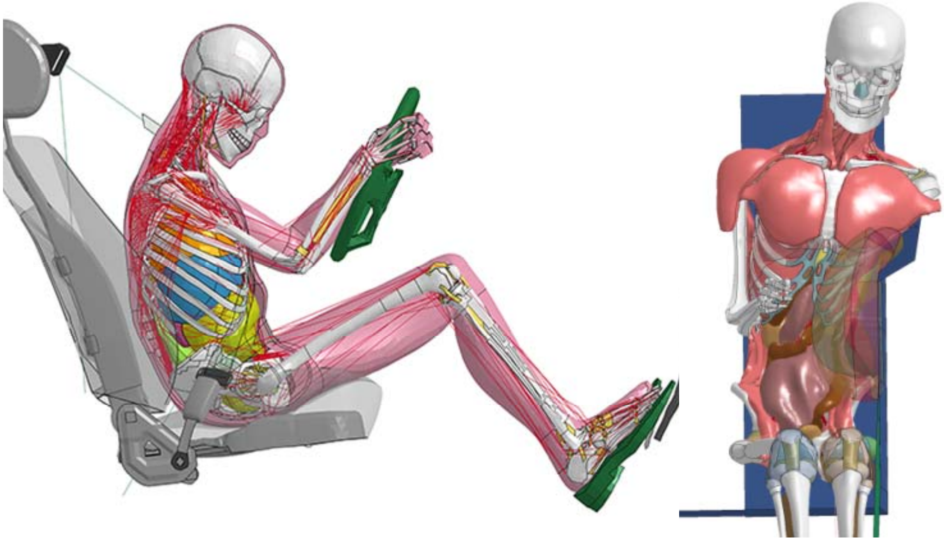


Figure 1: Examples of advanced HBM from the two leading model families. Left Thums in frontal impact and right: GHBMC model in side impact interaction with an airbag (sources: Toyota Newsroom http://newsroom.toyota.co.jp/en/detail/8487899 and UCBL-Ifsttar, respectively)

However, despite these improvements, these HBM are underutilized. While being relatively common in biomechanical research, applications in industrial R&D are more limited and they are absent from regulatory procedures and consumer evaluations, with the exception of the recent and limited introduction in the pedestrian EuroNCAP protocol. Multiple factors could be attributed to this relative lack of use:

1) *These HBM are difficult to use in real environments.* Occupant HBMs are typically only available in *one posture which is difficult to change*. Postural changes may require pre-simulations or global deformation approaches (e.g. mesh morphing) which can decrease the quality of the elements, lead to numerical instabilities and require re-meshing. This, coupled with the increasing model complexity and the lack of standard for positioning, makes the use of advanced models especially problematic for industrial R&D engineers without an advanced biomechanical knowledge.
2) *The human variability is insufficiently taken into account.* While one of their expected strength should be the ability to simulate any category of road users (e.g. children, young or elderly, male or female, tall or short, obese or underweight), HBM are only typically available for a few sizes corresponding to the dummies. The ability to simulate specific populations would enable new applications in industrial R&D, consumer testing or regulations. However, classic development methods are costly. Methods to generate population or subject specific models from a baseline by scaling/morphing are currently too limited, available only in research environments, and not standardized. Improving these methods and making them available would help in industrial R&D but also in research (e.g. by allowing

subject specific validation instead of using scaled corridors or by enabling more realistic simulations of real accidents to refine human tolerance).

3) Regarding active/integrated safety approaches, *advanced FE models are also difficult to use in the pre-crash phase of the event due to computing cost issues and difficulties to integrate the effects of active musculature or kinematic strategy* – which is critical for that phase. Currently, multi-body human models seem better suited for pre-crash because their low computing cost is compatible with the use of simplified muscles and controllers required by optimization strategies. However, these models show limitations in the high deceleration phase when the body segments deform and active musculature only plays a very small role. The combination of both approaches – rigid body for pre-crash and deformable/FE for crash – could therefore bring great benefits for active safety, but *requires initializing the advanced FE model in the posture at the onset of the high deceleration event*.
4) *The HBM are not standardized*, and various efforts have led to several incompatible model families (GHBMC, THUMS, HMODEL, HUMOS, Ford models, etc.). Improvements and new research knowledge acquired using a specific model does not benefit to the others. *This leads to a dilution of the efforts,* uneven performance and validation levels. This dilution is a factor limiting their acceptance, along with other difficulties already listed. New models should be limited in the future to baselines which could not be derived from existing models by scaling due to biomechanical specificities (e.g. children).

In summary, rather than new models for injury prediction – which would lead to further fragmentation of the research effort – it is believed that advanced positioning and personalization/scaling tools are critically needed to enable new applications for the advanced FE models in both industrial and research fields and solve some of the shortcomings mentioned previously. Particular attention should also be given to the issue of fragmentation and new tools should be largely model-independent.

## *2.2 Objectives*

The **main objective of the undertaken project is the development of advanced positioning and personalization/scaling methods and associated tools**. More specifically, the objectives are:

- To **specify the requirements for positioning and personalizing methods based on selected relevant automotive applications and feedback from possible users.**
- To **develop a framework for the positioning and the personalization/scaling that is mainly deformation based**. The approach will take into account explicitly anatomical/biomechanical functions in the process, as well as numerical quality metrics. It will be modular and allow the comparisons of approaches and fallback solutions.
- To **develop predictors for the posture and shape**. The aim is to be able to target specific populations based on limited knowledge, by choosing the most probable deformation or positioning target in the statistical sense.
- To **combine the posture and shape predictors and deformation methods** into an easy to use tool that will allow industrial and academic users to position and personalize models based on limited knowledge.
- To **evaluate the performance** of the tools and methods in these applications. This will help defining best practices for personalizing and positioning models for future industrial and research use. The applications will also provide preliminary biomechanical results (knowledge).

The **tools** will be developed and tested using **leading adult models** (from the THUMS and GHBMC families) and **child models. These child models will be** further developed based on preliminary work initiated in the CASPER EU project (2008-2012). This set of FE models with different levels of refinements are believed to be representative of the variety of Human body models that will be used in the coming years. The tools and methods will be developed based on the needs identified by key industry and academic partners, and they will be evaluated during the project in key usage scenario including **subject-specific validation** based on PMHS testing, **postural pre-crash,** where models will be moved to the positions resulting from the pre-crash phase, **accident reconstructions** (with child models that could be scaled, positioned and used in simulations of physical accident reconstructions).

**Results will be largely distributed at the end of the project using an Open Source dissemination strategy.** This strategy will be an integral objective of the project as having models available is not sufficient to ensure wide use. It is believed that some of the gaps are organizational in nature, and that a reflection is needed considering issues such as specification, reproducibility, need for openness in public procedures, and the current business/intellectual property models around HBM.

**In the end, the overall challenges that the project aims to address can be summarized as**

- **Challenge 1: A shift in dissemination and model licensing.** The project aims to change the current IP and dissemination model – that has led to fragmentation of the research effort, limited dissemination and use– by making tools that were developed during the project widely accessible to the community.
- **Challenge 2: Enabling new applications with HBM.** The project aims to enable new applications for human body models which are made difficult by the relative lack of positioning and personalizing tools, and limited models availability (in particular for child occupants and their environment within an accident reconstruction context).
- **Challenge 3: A novel framework to position and personalize models.** The project aims to develop new tools to position and personalize finite element models for impact. Besides the dissemination aspects, the tools aim to integrate within a single framework the ability to work with multiple models, transform them using state of the art positioning or personalizing modules driven by the user and export them.

# 3. Description of main S & T results/foregrounds

The main results of the project will be presented with the following outline:

- Specifications phase: overview of the feedback received from possible users and the priorities set
- PIPER Child Scalable model: design and validation
- PIPER Software Framework and Application: concepts, structures, modules and capability
- Summary of other results
- Applications of the PIPER framework and PIPER Scalable child model
- Summary and perspectives.

Note: all main results are already distributed online under an Open Source license. Links will be provided along the descriptions. A summary of all available results can be found at http://www.piper-project.eu or http://www.piper-project.org (will be updated after the EU project).

## *3.1 Specification phase and preliminary evaluations*

The development was initiated with a specification phase. As user acceptance is critical for the success of the PIPER framework, a systematic online survey was developed to collect information about current practices and interest of potential users. It included 60 questions and 32 explanatory graphics. The survey was successfully carried out and responses from 189 users were received. All results of the poll can be found on the PIPER website (http://www.piper-project.eu/media/survey/survey-analysis-231014-2.pdf) in an easy to understand graphical presentation. All questions received a substantial number of answers, allowing detailed analyses. More than 50% of the survey participants came from the industry, which shows the high interest in the use of HBMs in industry. The poll allowed to collect information about current model sizes (affecting the performance of needed for the software), current practice and time needed to position models, etc. Other key results included:

- ***The need for FE solver and model neutral approaches.*** As the framework aimed to be addressing the potential needs of the community, just selecting the most commonly used FE HBM, the most common solver and the most common operating system would result in excluding a large proportion of the potential users, which would then need to develop their own solution, hereby promoting fragmentation. This observation of the user diversity and the need for solver and model neutral (or agnostic) approaches had a strong effect on the Framework design.
- ***For scaling, the interest in global stature change,*** rather than localised model personalization.
- ***For positioning, an interest for realistic normal driver or passenger positions and the ability to perform parametric studies.*** A more complete list of priorities is provided as an example of results in Figure 2.

In parallel, *a priori* knowledge related to the definition of internal or external body shape or posture was reviewed and preliminary evaluations of various personalizing/scaling or positioning methods available at the project partners were conducted to help define a course of action.

The review of existing *a priori* knowledge put in evidence large amounts of data related to body shape in the form of regressions and 1D anthropometry. However, publicly available 3D shape data or more generally internal data usable for statistical analysis (e.g. using Principal Component Analyses) seemed scarce, especially at the full body level. Other findings suggested that existing postural knowledge (e.g. distribution of motion in the spinal levels) could be useful to help improve the realism of postural targets.

Regarding numerical methods for the transformation of HBMs, various interpolation functions were tested (including Moving Least Square – MLS - and Kriging/Radial Basis Function methods) as well as contour-based and lightweight physics-based (Open Source Sofa Framework, http://www.sofa-framework.org/) positioning approaches. When performing anthropometry changes on the GHBMC or child models (e.g. Figure 3), all interpolation methods could provide acceptable results in terms of time needed and element quality but there were significant differences in terms of cost. A detailed analysis was published in the Stapp Car Crash Journal (Jolivet et al., 2015). For positioning, light physics-based formulation seemed to be a promising approach to provide real-time realistic interaction models that respect many of the constraints from the FE HBM and that can then be used to drive the position change (e.g. Figure 3). Beyond numerical methods, the results highlighted the need for the model to be “positionable” (e.g. allowing soft tissue to follow the motion around the joints) in order to preserve the runability of the FE HBM model, i.e. an appropriate element quality without remeshing. These observations helped for the design of the PIPER child model.

This specification phase helped outline the main targets for expected features and capability, pre-select some numerical approaches, and technical implementation choices (C++, Python, Qt, Sofa Framework, targeting both Windows and Linux operating systems). It was also an important moment for the first contact with potential users.

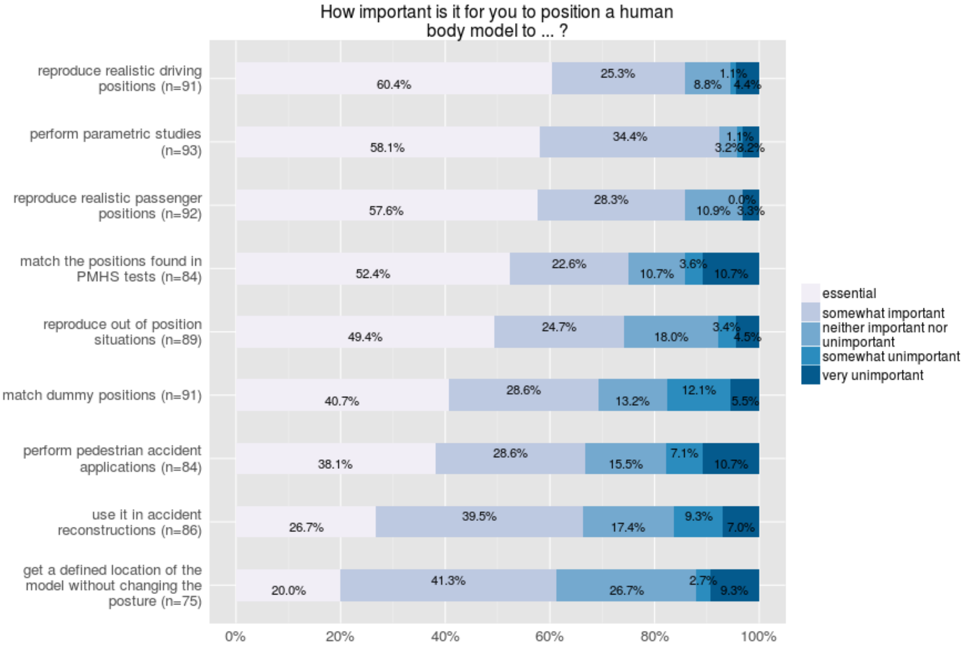


Figure 2: Example of answer related to positioning priorities in the user poll.

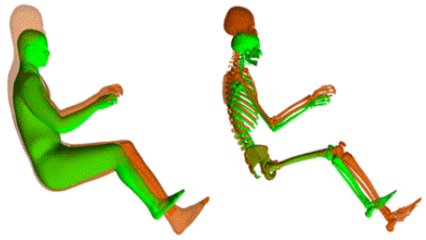


Figure 3: Example of stature change using MLS interpolation (GHBMC M50 to test subject anthropometry).

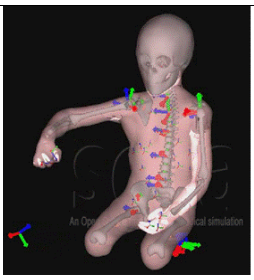


Figure 4: Shoulder positioning using the SOFA lightweight physics simulation (Child model: raising the right arm).

## 3.2 PIPER Scalable Child model

*Needs and challenges.* Paediatric impact biomechanics for road safety presents some unique challenges compared to the adult. The biomechanical structure and proportions of children differ significantly from those of adults (e.g. presence of growth cartilage, head to body size ratio) and, more importantly, these properties evolve quickly with age compared to the adult (e.g. 1.5 vs 10 y.o.). Over time, these changes have led to different protection strategies for children in cars with a variety of Child Restraint Systems (CRS) including rear facing CRS, forward facing harness or shield, booster seats and booster cushions used with the three point belt. This diversity of restraint conditions – again compared to the adult restrained by the three point belt – is challenging for the dummies which are currently used for the CRS assessment.

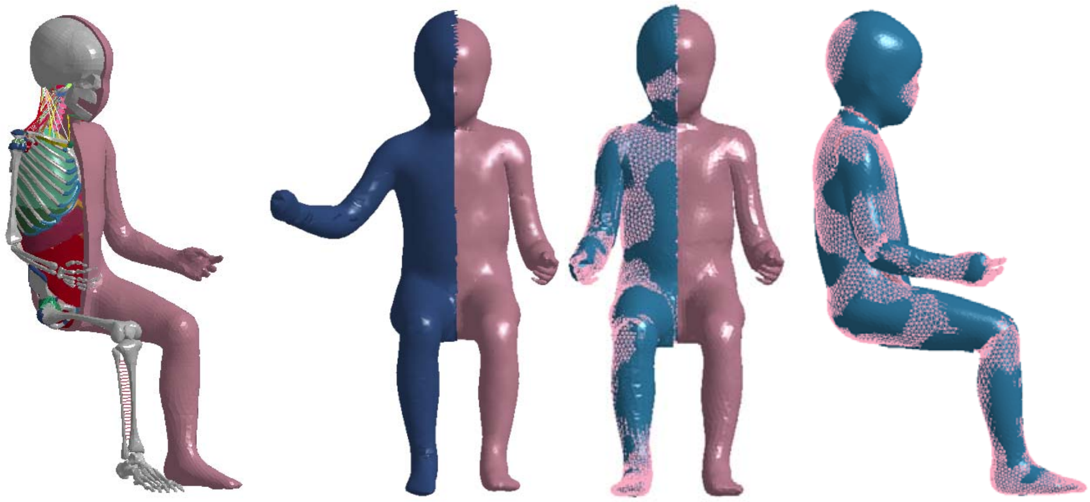
Because they are not subjected to the same limitations as the physical dummies and because they can describe the human anatomy on a more local scale up to the level of material properties, FE HBM of children have the potential to address some of the current shortcomings of dummies and to bring significant insight into the paediatric response to impact. They could better describe both variations due to age and size changes up to the material level, and they could have a better response to a diversity of loading configurations including in multiple directions (Omni directionality). However, the availability of child HBM has been more limited than adults. Existing models are typically only available for one age or size, while capturing the size change is desirable considering, for example, the recent regulatory approach in UNECE R129 where continuous size ranges can be specified by CRS manufacturers. Another difficulty is that the data available to check the response of such models is scarcer for children than for adults due to the more limited number of Post-Mortem Human Surrogate (PMHS) test results. While new studies have been published in the past few years, they are typically based on a small number of PMHS of different ages and characteristics. Checking the response of a model (or validating it as often formulated in the impact biomechanics field) could, therefore, require performing verifications at different ages.

Based on these observations, one of the objectives of the PIPER project was to develop and make widely available a new child model which could be scaled to follow the growth of children and whose response would be checked against PMHS data in many configurations and different directions (including frontal and side impact). The main targeted age range was limited to 1.5-6 y.o. (with possible extensions up to 10 y.o.) as it is it the main age range restrained in forward facing configuration.

This model, called the PIPER Scalable Child HBM, was released at the end of the project and is available online along with all simulation setups used to check its response at https://gitlab.inria.fr/piper/child. It was also used as a development HBM for the PIPER framework and it is fully supported by the PIPER framework (including a dedicated scaling module). The approach used for the development and the model performance are summarized below. It is also available in a video form at https://www.youtube.com/watch?v=g0svSsQ2-Vo. This work essentially performed as part of the Work Package 1 (KTH, UCBL, TUB) in close collaboration with other partners for the integration in the PIPER framework.

*Approach.* The developments were engaged using previous efforts initiated at UCBL-Ifsttar on the modelling of the trunk (CASPER EC project, 2008-2012) and of the whole body (ProETech French Projects, 2011-2014). The model, which could approximate known PMHS responses on frontal impact (with a focus on the trunk), had shown potential for the study of the kinematics and interaction with CRS (Beillas et al., Conf. Protection of Children in Cars 2013, 2014, Ircobi 2014). While corresponding to a 6 y.o. child dimensions, the model was scaled to dimensions of a 3 and a 1.5 y.o. child through Kriging interpolation. However the model had simplified pelvis, limbs, head and neck (rigid bones), without description of the growth cartilage nor isolated validation for the simplified segments or in side impact. For the PIPER project, the model was extensively modified (new head, neck, shoulder, pelvis, lower extremities, re-meshed abdomen, and adjusted skin envelope), deformable materials were introduced in many location (including growth cartilage), the validation was extended to all regions and to side impact, and the scaling techniques were improved.

*PIPER Scalable Child model overview.* The baseline model describes a 6 years old child whose main anthropometric dimensions were normalised by nonlinear scaling (kriging interpolation) using GEBOD (Cheng et al., 1994) regressions as a reference (stature: 1146 mm, seating height: 631mm, etc.). Overall, the internal geometry is based on a combination of several CT scans obtained from a children's Hospital under a data sharing agreement (Hospital *HFME,* Hospices Civils de Lyon, Bron, France) for children of different ages (1.5, 3 and 6 y.o.) prior to the project. Semi-automatic segmentations of the scans were used to define the bony and main organ shapes as well as the evolution of growth cartilage. These were complemented by anatomical descriptions for the placement of ligaments and other structures difficult to see on the CT scans. The only exception was the foot which was difficult to segment due to the large proportion of growth cartilage and that was derived from the scan of an elderly subject that was scaled to the child size. This was deemed as an acceptable assumption as the foot is still considered as a rigid component as it is not currently a point of focus in child safety. As the scans were performed in a supine position, a postural adjustment of the thoracic and lumbar spine was manually performed by tilting individual vertebrae to approximate the curvature obtained on a seated adult in Upright MRI data (Beillas et al., Stapp 2009). The skin was also mostly derived from the CT scans but the postural change required more adjustments: surfaces in different regions (e.g. head, neck, trunk, upper and lower extremities) were assembled in the target posture and the mesh continuity was obtained by interpolation. The trunk skin was deformed to follow the curvature changes. Data for seated subjects were provided by University of Michigan (OCATD 6YO dataset, and, more recently, seated shape based on statistical shape modelling) were used to complement the surface and help with the assembly. While these developments were performed in multiple model iterations, its spinal posture was kept. An illustration of the geometry of the final model is provided in Figure 5, along with comparisons with UMTRI seated statistical shape model (http://childshape.org). The PIPER shape was found to be plausible – within a few millimetres – to the UMTRI shape for similar anthropometric parameters. The PIPER Child model comprises approximately 546,000 elements (including about 52,000 rigid elements) distributed into 407 parts describing the main anatomical structures. It has a mass of 23kg (6 y.o. baseline). Material properties were derived from the literature. It was developed in the LS-DYNA explicit FE code. The model time step is 0.32 µs with marginal mass scaling (15 grams added). The model includes sensors similar to those present on dummies in order to facilitate future comparisons. Brief descriptions of the main anatomical regions are provided below.



a) PIPER scalable child model

b) Comparison with UMTRI shape (blue). Left: without postural adjustment. Right: with head and limbs from UMTRI shape aligned to the model skin.

Figure 5: Overview of the PIPER child model (at 6 y.o.) and comparison with UMTRI seated statistical shape model (1146 mm, BMI 17.05, SHS: 0.55; recline: 11; Flex: 50; http://childshape.org).

*Head.* The development of the PIPER head model described in Giordano and Kleiven (Ircobi 2016) was continued with significant updates made to the mesh. In accordance with the human anatomy, the brainstem was described with a cylindrical topology and the thickness of the scalp was adjusted to 5 mm on average (Loyd 2011). The final PIPER head model is shown in Figure 6. It consists of approximately 44,000 elements. A typical spatial resolution of 3–5 mm was chosen to capture fundamental anatomical structures but, at the same time, not too fine so as to guarantee a reasonable computational time.

*Neck.* The vertebral geometry is based on the segmentation performed by UCBL of a CT scan of a 3 y.o. child. The vertebrae were meshed with hexahedral elements for the cancellous bone and covered with shell elements for the cortical bone. The mesh topology was made elliptic to accommodate for a continuous mesh between vertebrae and intervertebral disks. The topology was also designed to allow for three layers of shell elements to be embedded in the intervertebral disk to represent the annulus fibres, whereas the annulus ground substance was modelled with solid elements. At the centre of the disks, solid elements represented the nucleus pulposus. The typical element size of around 2 mm was needed to capture necessary features of the spine. It resulted in about 25,000 elements (Figure 7), including ligaments and neck muscles (mostly discrete springs). The 3 y.o. mesh was scaled to the 6 y.o. using the PIPER scaling approach.

*Trunk (thoraco-abdominal and pelvic regions).* While the overall shape was kept, extensive changes were performed for the pelvis and soft organs. The pelvis was meshed with deformable elements describing cancellous and cortical bone (tetrahedral and shell elements), as well as growth cartilage. The thoraco-lumbar spine (rigid vertebrae connected by 6 d.o.f. beams) was partially remeshed. The ribcage is still described by deformable elements for the ribs (connected to the spine by 6 d.o.f. beams at the costo-vertebral joint), costal cartilage and sternum. The thoraco-abdominal cavity is separated by the diaphragm whose insertions on the spine and lower ribcage were improved. Muscles of the abdominal wall and retroperitoneal tissues were separated from the former flesh components to provide more accurate anatomical boundaries for the abdominal cavity. The shapes of liver, spleen and kidneys were smoothed, and a pancreatic component (pancreas and surrounding fat) was introduced. The small intestines and colon are not separated and are described using an incompressible bag (unchanged). An incompressible bag formulation is used for the heart, whose geometry was modified to better describe the overall organ shape. The lungs remain as compressible bags. In general, non-sliding/attached relationships are described using continuous mesh between parts, while sliding relationships are described with sliding contacts. Gaps between organs were reduced. The trunk model is shown in Figure 8.

*Upper and lower extremities*

Both extremities were extensively updated in the project and use similar modelling approaches. They use deformable elements for bones and ligaments up to the distal end of the humeral diaphysis and femoral diaphysis, and contacts for the shoulder and hip joints to allow for load transfer in side impact. The distal humerus, radius and cubitus, distal femur, proximal tibia and patella, and distal tibia are modelled as rigid bodies (one for each). Elbow, wrist, knee and ankle joints are using 6 d.o.f. beams. Hands and feet are modelled using rigid bodies. For the lower extremities, diaphyseal thicknesses were adjusted based on the segmentation. An illustration is provided in Figure 9.

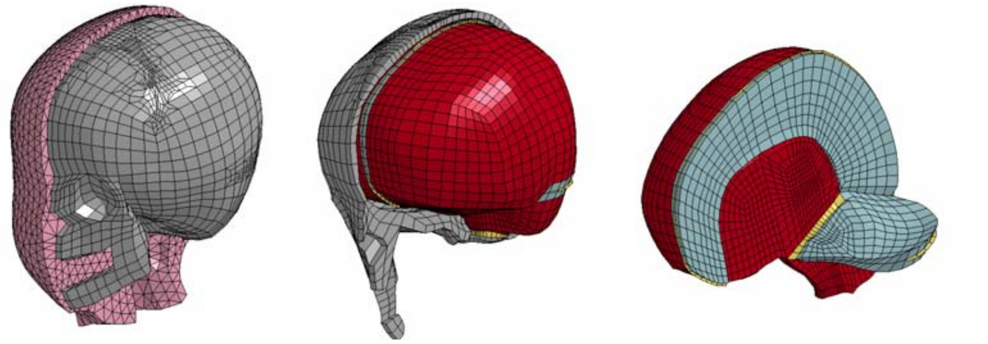


Figure 6: PIPER Child Head Model including descriptions of the scalp, skull, cerebrum, cerebellum, meninges and cerebrospinal fluid. From left to right: head model with open scalp for visualisation of the skull; head model with open skull for visualisation of the brain; head model with open brain for visualisation of the meninges.

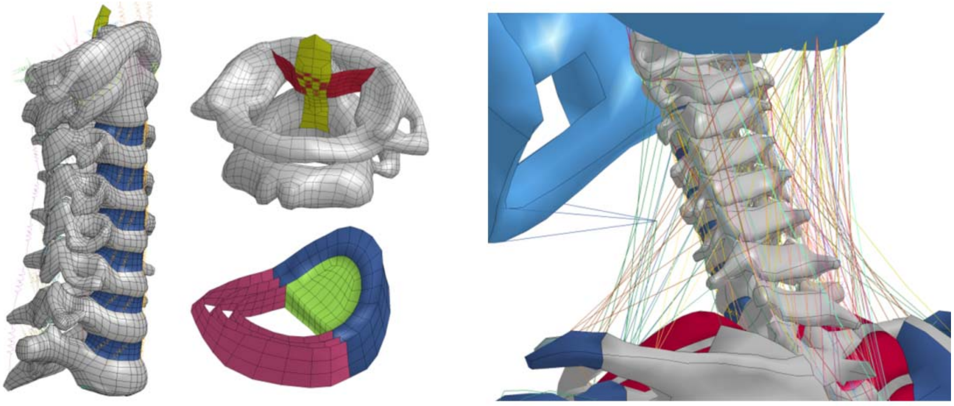


Figure 7: Neck model, visualising the ligamentous spine (left), C1-C2 with shell ligaments and intervertebral disk (middle) and surrounding muscles with attachments (right).

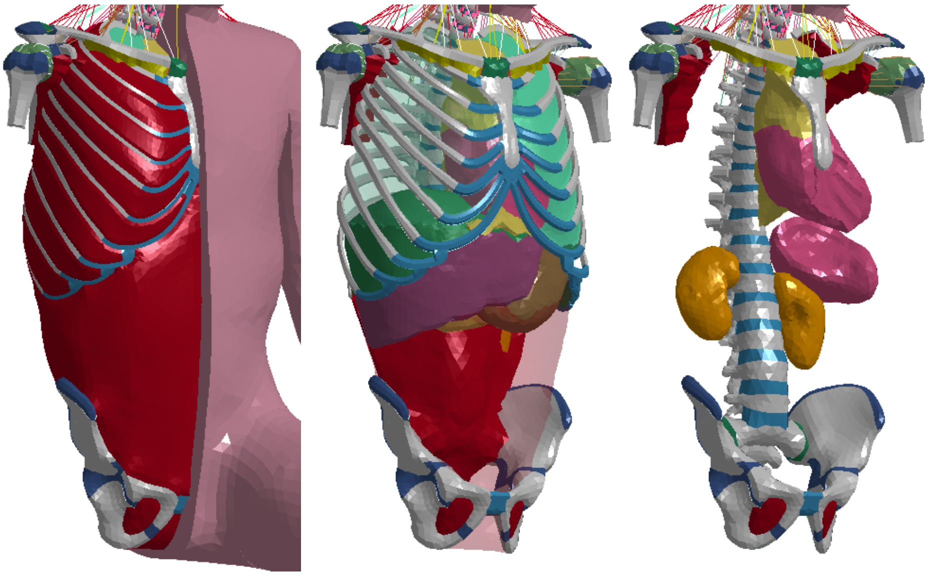


Figure 8: Overview of the trunk (thorax abdomen pelvis) with the skeleton (grey), cartilage (blue). From left to right: skin and flesh removed to show abdominal and intercostal muscles (red). Center: muscles removed and right lung and hollow organ bags partially transparent to expose the new retroperitoneal component (red). Visible structures include the new diaphragm (green), liver (purple), stomach and pancreatic component (light and dark brown). Right: kidneys, spleen and updated heart.

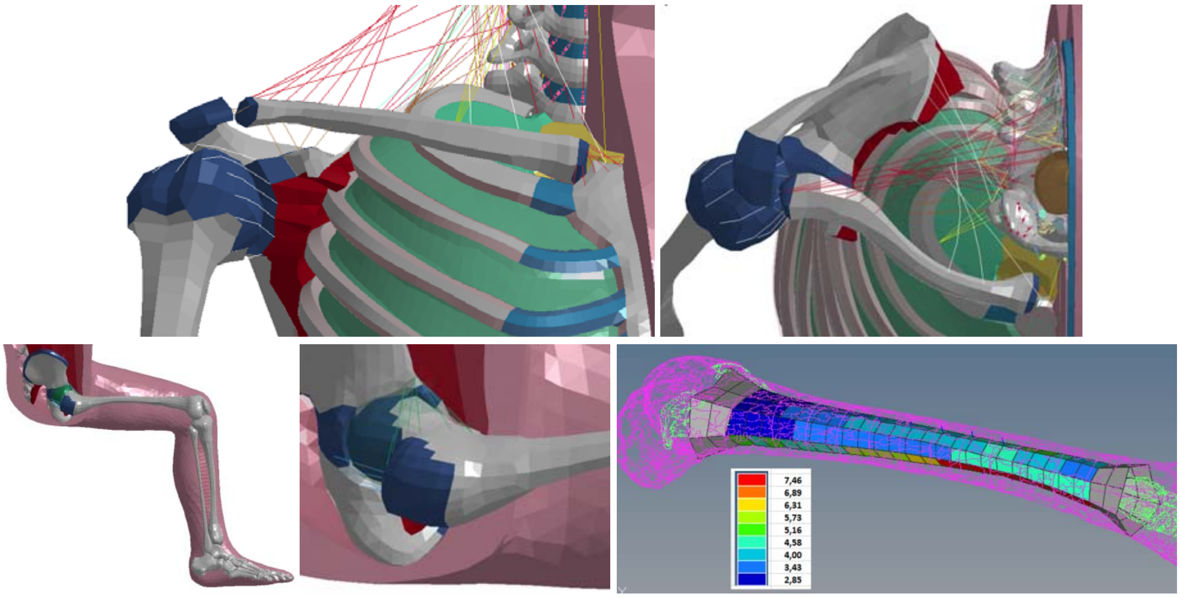
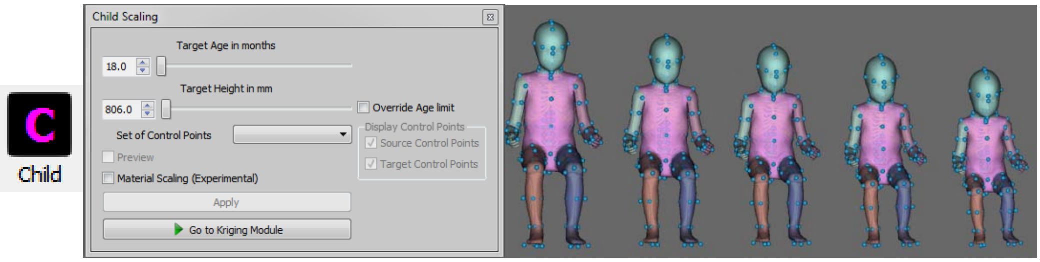


Figure 9: Top: details of the shoulder model. The clavicle can slide over the thorax (red surface) and components are deformable (bone in grey, cartilage in blue). Bottom: lower extremity model with deformable hip and thickness map used for the femoral diaphysis.

*Metadata and PIPER framework integration: age scaling and positioning.* The PIPER child model was one of the development models for the PIPER framework. The model can be used in positioning and scaling applications (support for all modules except spine curvature which is driven by adult specific data). The child model also has features to facilitate its positioning using the pre-positioning module (e.g. capsules around the elbows and knees).

The child also has its own dedicated module for stature and age scaling. It is an evolution of the previous work on scaling based on anthropometric dimensions from GEBOD that was further developed to include some local constraints. More specifically, regressions based on GEBOD are used to compute anthropometric dimensions, represented by a network of control points used to drive the model morphing. The regressions were typically used between 6 and 1.5 years old (using extrapolation between 2 and 1.5 years old) but are also valid above 6 y.o. Additional constraints were added to the head (to account for variations in head segments' proportions with age) and neck (to help drive the change of local features such as the angle of the facet joints). The module also allows updating material parameters that are age dependent (based on regressions from the literature). This feature is experimental as the validations simulations were not re-run with this material scaling. The module is implemented using Octave and Python scripts (to define the dimensional or material targets) that were integrated in the PIPER framework (Figure 10).



Target Age in months 18.0

Target Height in mm 806.0

☐ Override Age limit

Set of Control Points

☐ Preview

☐ Material Scaling (Experimental)

Display Control Points

☑ Source Control Points

☑ Target Control Points

Figure 10: The PIPER child model has its own Child scaling module integrated in the PIPER application. From left to right: Icon, menu allowing to select the target age or height (geometric scaling) as well as the optional material scaling, examples of scaled models with the network of control points visible (here in PIPER application GUI). The scaled models can be run without error (when using a nugget parameter for the smaller ages).

*Model validation.* The targeted validation matrix (Table 1) was compiled based on various literature sources. It includes mostly results collected on paediatric PMHS, and it covers regional response (e.g. head), global kinematics (sleds), frontal and side impact. Some setups were also included to allow comparisons with the dummies. Some simulations were run at different ages.

Examples of a few simulations results for different regions are provided in Figure 11 for simulations using parts of the model, and Figure 12 for simulation using the full model (regional impacts on the trunk or sled kinematics). In general, the responses were found to be close to the experimental reference curves (or within the experimental variation).

Some discrepancies could be observed for example in side impact. These discrepancies were investigated in detail (an example will be shown in the application section) and will be the subject of a dedicated publication. Perspectives would include accounting for material scaling, simulations for a few more ages available in the reference studies, and the personalization of the model to each of the test subjects to investigate which part of the experimental variation could be explained by dimensional and material scaling. **In the meantime, the model was found to interpolate well between datasets from very heterogeneous sources, suggesting that it can approximate the response in many loading conditions and for a validation matrix that we believe is the larger of any child model to date.**

In order to facilitate future evolutions, the input files were structured such that all simulations can be rerun easily after modifying the model (including for regional setups including the head or neck) and all results can be post-processed automatically using a set of python scripts and digitized experimental data (delivered with the model). The only exception is the lower extremity diaphysis bending which has to be run separately. This approach should widely facilitate future comparisons and model evolutions by setting a reference for the model performance. Correlation scores (e.g. CORA) should also be computed in the future to facilitate the performance tracking.

Table 1: Overview of the 23 setups in the final validation matrix

| Published Study | ROI | Dir | Impactor/loading | Subjects and ages | | Target model |
|---|---|---|---|---|---|---|
| Loyd (2011) | Head | Regional | Drop test (dyn) | PMHS | 9, 1.5 | 6, 1.5 |
| Loyd (2011) | Head | Regional | Compression (dyn) | PMHS | 9 | 6 |
| Ouyang et al. (2005) | Neck | Regional | Bending + tensile | PMHS | 6 | 6 |
| Luck et al. (2008) | Neck | Regional | Tensile | PMHS | 6 | 6 |
| EEVC Q (2008) | Shoulder | Side | Pendulum, free back (dyn) Scaled | PMHS | Adult | 6, 3 |
| Ouyang et al (2006) | Thorax | Frontal | Pendulum, free back (dyn) | PMHS | various | 6, 3, 1.5 |
| Kent et al (2011) | Thorax | Frontal | Belt distributed, fixed back (dyn) | PMHS | 6 & 7 | 6 |
| Kent et al (2011) | Thorax | Frontal | Belt diagonal, fixed back (dyn) | PMHS | 6 & 7 | 6 |
| EEVC Q (2008) | Abdo | Frontal | Belt, fixed back Scaled corr. | Porcine | 6 | 6 |
| Kent et al (2011) | Abdo | Frontal | Belt mid abdo, fixed back (dyn) | PMHS | 6 & 7 | 6 |
| Kent et al (2011) | Abdo | Frontal | Belt upper abdo, fixed back | PMHS | 6 & 7 | 6 |
| Part 572 | Lumbar | Frontal | Torso flexion (static) | HIII | 6 | 6 |
| Ouyang et al (2003a) | Pelvis | Side | Pendulum, free back (dyn) | PMHS | various | 6, 3 |
| Ouyang et al. (2003b) | Femur | Regional | Bending test | PMHS | | |
| Wismans et al (1979) | WB neck | Frontal | Sled test, harness (4 YO anthro) | PMHS | 6 | 6 |
| Kallieris et al (1976) | WB | Frontal | Sled test with shield | PMHS | 2.5, 6 | |
| Lopez et al (2011) | WB spine | Frontal | Sled test with belt (dyn) | Volunteer | | 6 |
| Arbogast et al (2009) | WB neck | Frontal | Sled test, 3pt belt | Volunteer | 6+ | 6 |

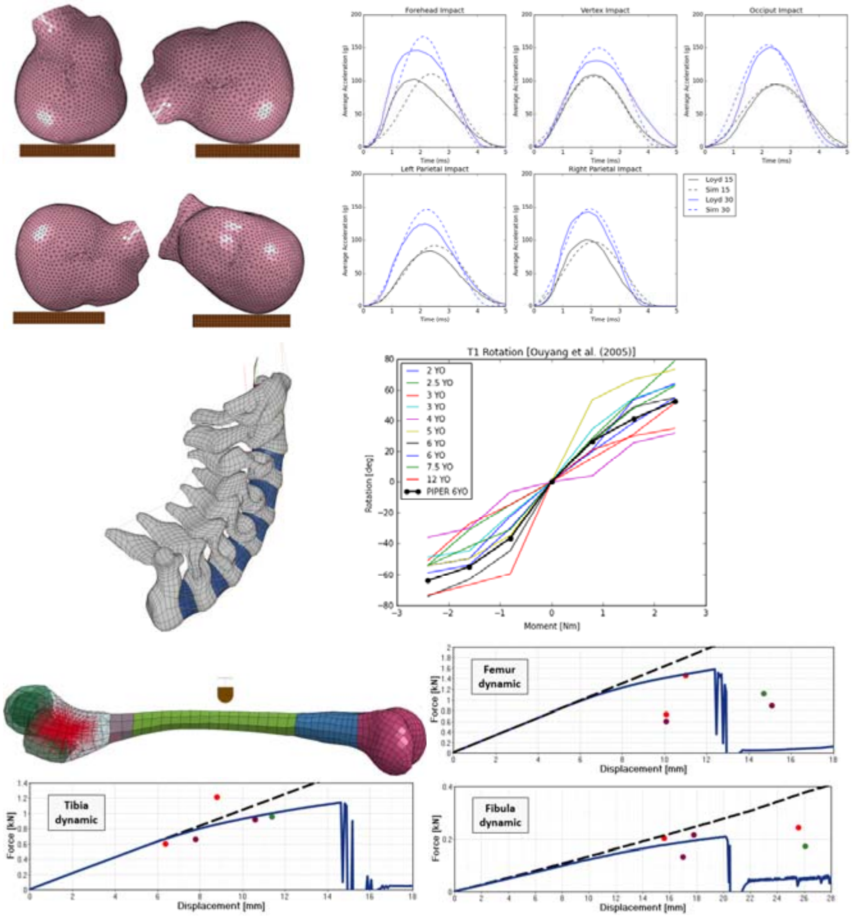


Figure 11: Examples of simulation results for the isolated region setups (6 y.o.). Top: head drop. Middle: neck flexion. Bottom: diaphysis bending. All setups use PMHS data as reference.

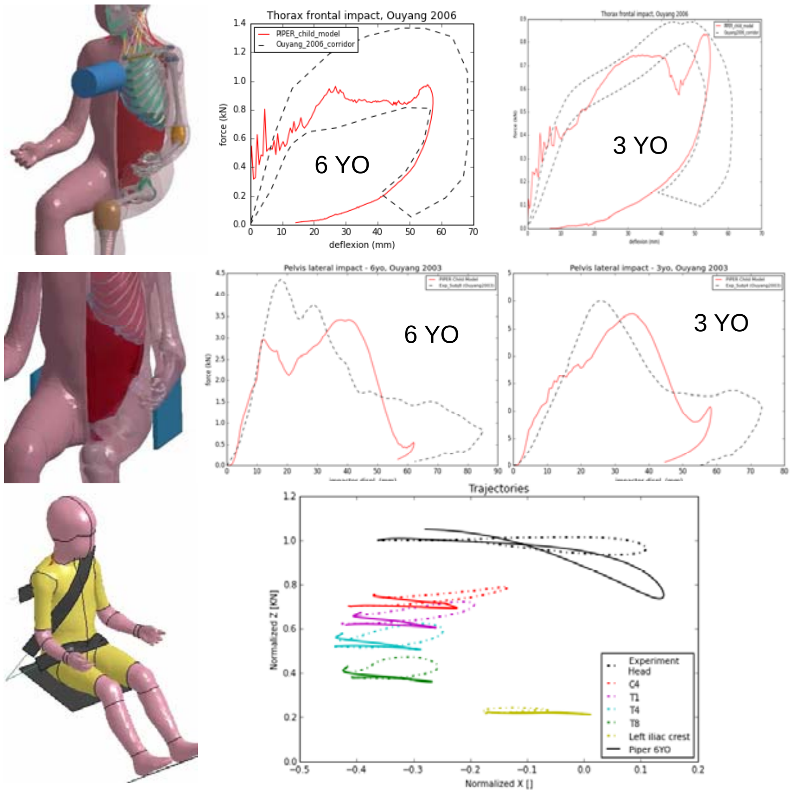


Figure 12: Examples of simulation results using the full body (6 y.o.) for regional impacts on the thorax (top, reference curves: PMHS) or the hip in side impact (middle, reference: PMHS), or for full body sled tests (bottom, model shown with the colour of a dummy, reference curves: volunteer tests).

**Conclusions on the PIPER Child model**

**The work on the first version (v1.0.0) of the PIPER scalable child model is now completed and the model was publicly released under an Open Source license** (with all contributions detailed in the file released). Its baseline version describes a 6 y.o. child that is continuously scalable to represent children of other dimensions (1.5 to 6 y.o, and beyond) within the PIPER application using a dedicated module. The model is deformable in all most relevant anatomical regions for injury prediction. Its response was checked against 23 setups from the literature including different ages. While not being exhaustive, this set represents **a large proportion of all data sources of the literature** and the widest used for any child model to our knowledge. No numerical stability issue was encountered during all the simulation configurations related to evaluate its behaviour. The response was found close to the experimental data in most cases, suggesting that the **model can be used to approximate the paediatric response in a variety of impact conditions** (or that it can represent a large part of the current biomechanical knowledge about the paediatric impact response). A few discrepancies were observed in some setups and investigated. Some behaviours observed in the application phase after the model release will also need to be investigated (e.g. stiffness of the hip). However, because of its scalable aspects, PIPER integration and scope of its validation matrix, we believe that the model represents a new state of the art for the age range and that many applications could already be developed based on it (study of kinematics, comparison with dummies, interactions with restrain systems, etc.). The most significant development perspective would now be to use the model in simulated accident reconstructions in order to build field base injury risk curves and to extend the model use to injury prediction.

## *3.3 PIPER Software framework and application*

*Concept, philosophy and definition.* Following the specification phase, the PIPER framework and application were developed within the Work Package 2 and 3. The basic idea behind the framework was that, since HBMs for impact were similar in terms of contents (as they describe anatomical structures, bones, soft tissues, use contacts, etc.), numerical methods, data and process used for scaling and positioning could be shared between them. This could **remove the need for re-implementation** for each new modelling task, and could **lead to more reproducibility** (between users and models). Also, it was realized that positioning or scaling are essentially driven or constrained by anatomy, physiology, or statistics. This **type or knowledge is not necessarily expressed in a FE HBM** which is specifically designed for its response under impact and at high accelerations. Starting from the specifications, the philosophy of the framework evolved and was refined along the project. Its key elements are:

- **Provide an open, modular platform (framework)** that deals with input/outputs, interface and display (interactive), and in which *a priori* knowledge and numerical methods relevant for positioning and scaling can be implemented as modules.
- **Be model and code agnostic:** be able to work with any model and simulation code without need for re-implementation inside the framework. The users are diverse and should not be excluded.
- **Do not tell users how to do their job** but try to help them. There is currently variety of practices (models designs, solvers, approaches). These should be respected, and new methods corresponding to these practices could be added in the future. Possibilities should be given, which could mean several modules for the same task. Future comparisons by users will likely decide what the best options are.

**The PIPER software framework and the PIPER application were built trying to follow these principles.** By software framework, it is meant that we attempted to formalize some of the concepts needed to position and scale an arbitrary model (model interpretation, anatomical vocabulary, target definition, model transformation, etc.) and that we tried to provide corresponding functionalities (through modules and libraries) that could be re-used to facilitate the development of the positioning and scaling software. All these functionalities are made available to the user through the PIPER application, which provide a Graphical User Interface (GUI) to facilitate user interactions. **All were released under the same license (GPL version 2 or later) and are already available online**. Key elements of the solutions implemented are provided below.

*Framework concepts: metadata, PIPER model, module and target.* One of the first challenges was the need to import the FE HBM inside the PIPER framework for transformation. There is typically nothing in the FE format linking an entity to an anatomical structure. For example, while there are keywords indicating what an airbag or a spot-weld is, there is no keyword to indicate that something is a bone, a femur, or the head. Model authors make their best to use descriptive names but there is no standard for that either. In the end, to be able to perform a transformation, it is desirable to associate some of the FE entities to anatomical concepts useful for scaling or positioning (e.g. a bone is not expected to deform during positioning as opposed to the skin). This leads to the following solutions and structure for the framework:

- Only the concepts relevant for the transformation need to be imported in the framework (e.g. geometry, anatomy). Once imported, the data actually represents a type of model relevant for positioning and scaling. This model is called a *PIPER model* (created dynamically at import).

- To associate the FE HBM's relevant concepts to a PIPER model in a generic way (i.e. respecting the requirements for model and solver agnosticism, and avoiding using intellectual property related to the HBM or solver inside the framework), *PIPER metadata* were created. These **metadata, that only need to be defined once for a given FE HBM model, associate the FE entities to PIPER concepts**. To try to standardize the names of the anatomical concepts, a database (so called *AnatomyDB*) containing vocabulary and relationships between anatomical entities was developed and is provided with the PIPER framework. For the implementation, an xml rule based language was created such that the user can specify what needs to be interpreted in the FE HBM (essentially the geometry and anatomy) as well as the basic description of the solver format. These files can be modified without recompiling the software.
- Once the FE HBM is imported, the resulting *PIPER model* can be transformed. The **transformations are performed by *modules*** that implement specific numerical methods or that interact with *a priori* knowledge. Multiple modules can be chained.
- The aim of the modules is to bring the *PIPER model* closer to the *(PIPER) target* desired by the user. However, the users often need assistance to refine the definition of the target: for example, the poll suggested that users were interested in global anthropometry changes (e.g. stature or BMI) but they do not typically know how every dimension of the human body should evolve with such changes. Thus **modules can also be used to refine the user target** (e.g. using correlations between what the user would like and more local metrics required for transformation).
- In the end, the *PIPER metadata* can be used to update the model.
- All user intentions or interactions can be done in a GUI or in batch mode (partially implemented).

Thus, with these concepts defined, a graphical overview of the PIPER framework and application is provided in Figure 13.

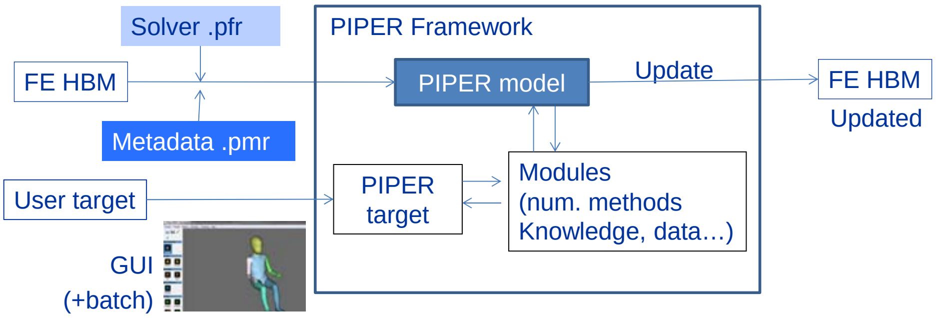


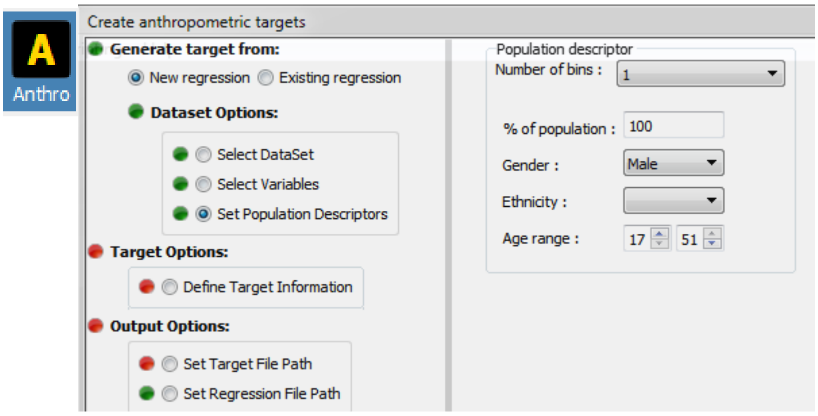
Figure 13: Overview of the PIPER framework and application. The use of external metadata and solver rule files prevents from putting any intellectual property from the FE HBM or the solver inside the framework, and enables HBM and solver neutrality. Modules can update the PIPER model (generated at import) and/or refine the target. New users can implement new modules and benefit from the overall developed infrastructure due to the independence of the framework from the solver of the HBM.

**The framework was successfully used with multiple (leading) HBMs** in the development and application phases (GHBMC M50 Occupant detailed, GHBMC M50 Pedestrian Simplified, Thums V3 and V4.02 AM50 Occupant, PIPER Child model, ViVA model) in the Ls-Dyna code. Preliminary tests were also performed with a Pamcrash version of the GHBMC M50. Some of these metadata were created by mechanical engineers without programming skills, and the models tested include the biggest HBM currently used in the field (in terms of element numbers). As such, this confirms the suitability of the selected framework structure to achieve model agnosticism.

*Implementation and PIPER GUI.* For performance reasons, the software framework and application is programmed in C++ and use strong open source libraries (e.g. Eigen, Sofa Framework, VTK display and processing, QT GUI). However, to make it more accessible to engineers, it also provides scripting interfaces in Python (with access to internal variables) and an Octave interpreter (as Matlab is widely used within the community). The PIPER GUI allows interactions with the users. It includes a display (based on VTK or Sofa in some modules) allowing to visualize the FE model, the PIPER model, metadata, etc. Most modules' parameters are also exposed in the GUI and can be changed interactively. Basic metadata can be also created and the mesh quality computed and displayed. Python script can be launched interactively allowing to modify the current PIPER model. Some of the key modules (created either by WP2 or WP3) will be briefly described and illustrated hereafter.

*Check module.* The check module provides textual information about the import of the HBM in PIPER (what was recognized and how it was interpreted etc.). It is the default module when a HBM is imported or a project is open.

*Anthropometric prediction module.* The module allows **predicting a set of anthropometric measurements using an arbitrary set of descriptors**, all measurements and predictors being in the same database. Therefore, it allows refining the target based on a limited set of user inputs. The calculations are made by a set of Octave scripts interfaced with the PIPER application through interactive menus. Some parameters are not implemented in the GUI but are available in the code. All regressions and statistical calculations are performed dynamically based on anthropometric databases. Three public databases covering different populations (Snyder for children, ANSUR for fit adult, CCTanthro for elderly subjects) are provided with PIPER but others could be added. An illustration of the GUI is provided. The module is used in several scaling applications and workflows (e.g. pedestrian). The module also includes a small functionality to compute anthropometry using the GEBOD regressions. Scaling using a bony landmark-based statistical model is currently being considered as an experimental feature.


Create anthropometric targets

Generate target from: ● New regression ○ Existing regression

Dataset Options:
○ Select DataSet
○ Select Variables
● Set Population Descriptors

Target Options:
○ Define Target Information

Output Options:
○ Set Target File Path
○ Set Regression File Path

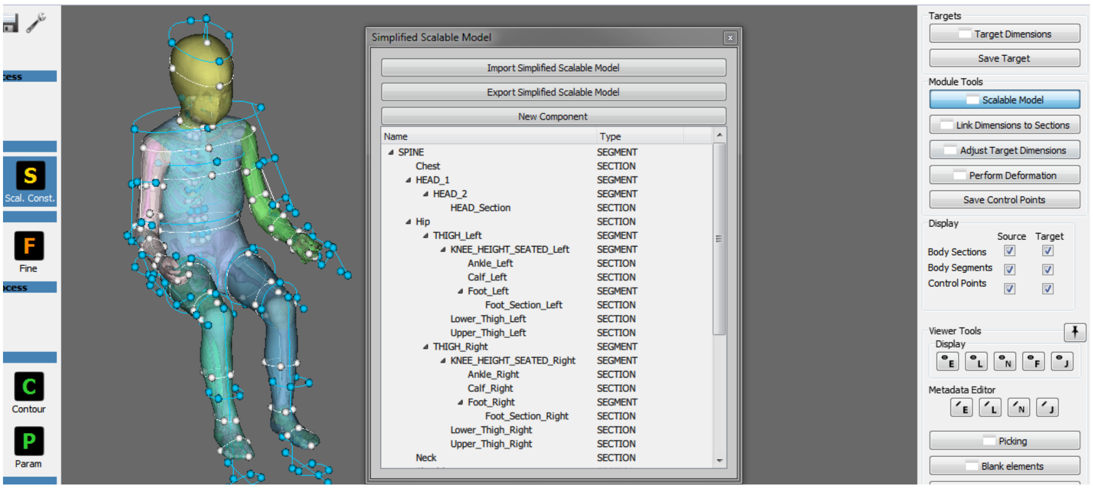
Population descriptor
Number of bins : 1
% of population : 100
Gender : Male
Ethnicity :
Age range : 17 51

Figure 14: Anthropometric prediction module. Many parameters can be defined in the GUI, from the population to be used for the prediction up to the type of predicted target (mean subject, or statistical distribution).

*Scaling constraint module.* The scaling constraint module allows **establishing correspondences between anthropometric dimensions and the HBM**. This is an essential and required step before scaling that was typically made manually and without visual feedback prior to PIPER. The module proposes a complete system to facilitate this work with:

- The definition of simplified scalable models, stored in xml files, that can be updated dynamically when dimensions are changed. The model allows representing circumferences, lengths, etc. in a hierarchical manner. The model is defined using landmarks, and circumferences are computed by intersection with the skin of the HBM.
- Functionalities to create, modify, update the simplified model and display it over the HBM.
- Functionalities to import, apply and modify (adjust values) the target dimensions (that can be created in the Anthropometry module or elsewhere).
- The ability to define control points required for kriging interpolation and to adjust their position on the simplified scalable model. An association parameter (*use_for_bone*, *use_for_skin*) can also be defined to use control points selectively for bone or skin scaling.

An illustration of the GUI is provided Figure 15. The module is used in several scaling applications and workflows (e.g. pedestrian scaling, child scaling in relation to UNECE regulation R129).



| Name | Type |
|---|---|
| SPINE | SEGMENT |
| Chest | SECTION |
| HEAD_1 | SEGMENT |
| HEAD_2 | SEGMENT |
| HEAD_Section | SECTION |
| Hip | SECTION |
| THIGH_Left | SEGMENT |
| KNEE_HEIGHT_SEATED_Left | SEGMENT |
| Ankle_Left | SECTION |
| Calf_Left | SECTION |
| Foot_Left | SEGMENT |
| Foot_Section_Left | SECTION |
| Lower_Thigh_Left | SECTION |
| Upper_Thigh_Left | SECTION |
| THIGH_Right | SEGMENT |
| KNEE_HEIGHT_SEATED_Right | SEGMENT |
| Ankle_Right | SECTION |
| Calf_Right | SECTION |
| Foot_Right | SEGMENT |
| Foot_Section_Right | SECTION |
| Lower_Thigh_Right | SECTION |
| Upper_Thigh_Right | SECTION |
| Neck | SECTION |

Display

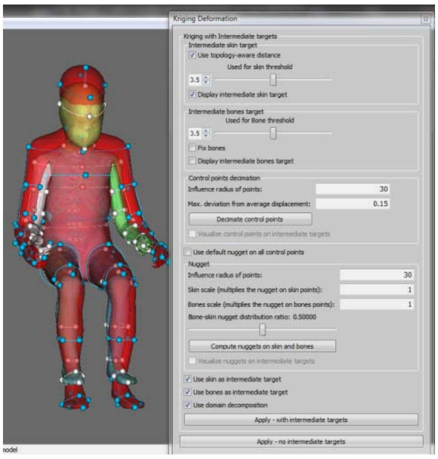
| | Source | Target |
|---|---|---|
| Body Sections | ☑ | ☑ |
| Body Segments | ☑ | ☑ |
| Control Points | ☑ | ☑ |

Figure 15: Scaling constraint module, shown here with the PIPER child model and a simplified scalable model linking it the Snyder database dimensions.

*Kriging module for scaling.* The kriging module provides a **nonlinear interpolation method to transform (morph) the HBM** once control points are defined. These points can be computed using the scaling constraint module, imported in the target format, or as simple text files). The module provides many options to drive the transformation. These include among others:

- Basic scaling (using the control points as is), scaling of the bone and skin independently (using different sets of control point selected using the association parameters), scaling the whole model using the skin and bone surfaces as intermediate targets.
- The use of Euclidian or surface distance in the kriging formulation
- The ability to define spatial domains that are scaled independently from one another
- An automatic space splitting option that allows using an arbitrary number of control points (linearization of the computational cost to deal with a large set of control points)
- Various options to adjust the transformation smoothing (nugget as a smooth parameter) and to down sample the control points (based on sensitivity, potential for penetration, etc.).
- A GUI to define the previous various parameters, and perform a quick preview of the skin or bone surface (Figure 16).

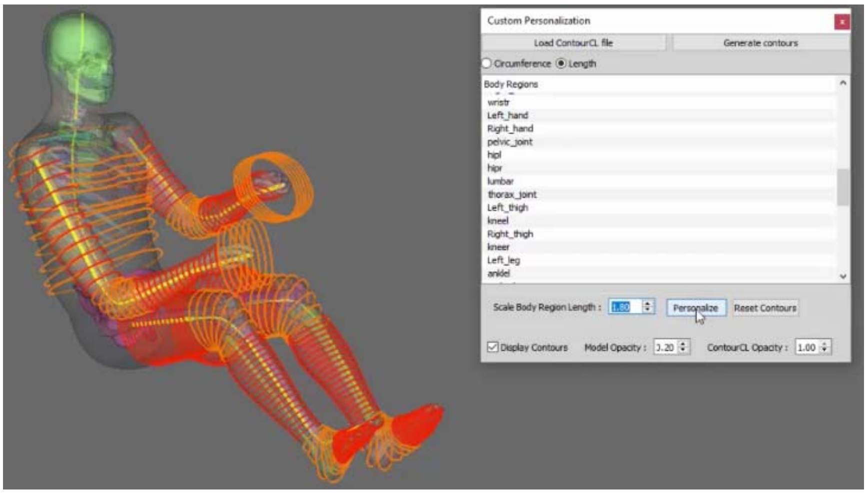
The kriging can be called in a standalone manner or within the scaling constraint module. It is used in several scaling applications and workflows. Publications are being prepared for some of the features implemented.



Kriging with Intermediate targets
Intermediate skin target
☑ Use topology-aware distance
Used for skin threshold: 0.5
☑ Display intermediate skin target
Intermediate bones target
Used for Bone threshold: 0.5
☐ Fix bones
☐ Display intermediate bones target
Control points decimation
Influence radius of points: 30
Max. deviation from average displacement: 0.15
☐ Visualize control points on intermediate targets
☐ Use default nugget on all control points
Nugget
Influence radius of points: 30
Skin scale (multiplies the nugget on skin points): 1
Bones scale (multiplies the nugget on bones points): 1
Bone-skin nugget distribution ratio: 0.50000
☐ Visualize nuggets on intermediate targets
☑ Use skin as intermediate target
☑ Use bones as intermediate target
☑ Use domain decomposition

Figure 16: Kriging Module GUI shown with the child model before and after transformation (corresponding to control points presented in Figure 15).

*Scaling using contour tool.* The scaling using contour tool allows transforming the model through contours positioned around the HBM. The contours can be updated using anthropometric dimensions and then used to drive the non-linear interpolation to transform the model (using Delaunay triangulation for the interpolation; see Figure 17 for illustration). The contours are defined based on metadata which are currently available for the GHBMC M50-O and as an experimental feature for the PIPER child model.



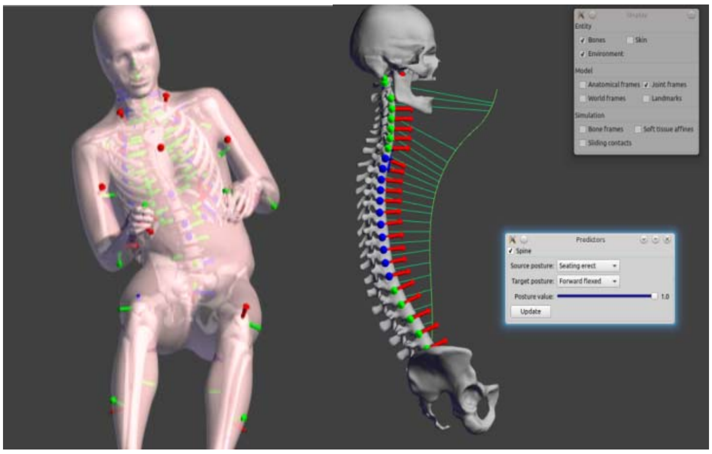
○ Circumference ● Length

Scale Body Region Length : 1.80

☑ Display Contours Model Opacity : 0.20 ContourCL Opacity : 1.00

Figure 17: Contours shown in the scaling module defined from the contour module applied to the GHBMC M50-O.

*Pre-positioning module.* The prepositioning module is used at the starting point of many positioning tasks. It uses **lightweight physics simulation** based on the Sofa Framework to change the position of the model interactively. This is **a fast (interactive), realistic, meshless simulation** approach coming from the world of computer graphics. Bones are simulated as rigid bodies and soft tissues are simplified using a limited number of degrees of freedom. Bones can be articulated using robotic joints or contacts. The simulation model is first built using the information in the metadata (including bones, joints, collisions, contacts, capsules, and a simplified representation of the soft tissues). The model can then interact with user constraints through controllers allowing the user to define targets for landmark positions, bones, joints etc. It can **also interact with *a priori* knowledge** to improve the realism of the transformation. For now, this capability is illustrated by the spine predictor module which allows attracting the spine towards spine postures derived from physiological databases and interpolated using splines (Figure 18). Other types of data interactions could be integrated such as pre-crash response, etc.



☑ Bones ☐ Skin
☑ Environment
☐ Anatomical frames ☑ Joint frames
☐ World frames ☐ Landmarks
☐ Bone frames ☐ Soft tissue affines
☐ Sliding contacts

☑ Spine
Source posture: Seating erect
Target posture: Forward flexed
Posture value: 1.0

Figure 18: GHBMC model posture change (left) and spine predictor module (right). Most positioning tasks start with this module.

After an acceptable target position is reached, the user has several options which are to be selected depending on the amplitude of motion, skin and element quality, availability of metadata, etc.:

- Update directly the FE model node positions (using interpolation functions),
- Use the target position (landmark, bone position, etc.) in the *fine positioning module*: this module uses the same methodology as *pre-positioning* but parameters for the Sofa simulation are changed

to refine the soft tissue modelling, resulting typically in more realistic skin surface at the expense of a longer time to initiate the module and a slight reduction in the interactivity.

- Use the target position (landmark, bone position, etc.) in the contour module.
- Export a valid input for a FE simulation where the boundary conditions are automatically generated and pull the HBM bones from its initial position to the one resulting from the prepositioning.

Overall, this innovative module provides a **user interactive workbench for the combination between model constraints (e.g. geometry, contacts, joints), user defined constraints (e.g. landmark position, angle) and *a priori* constraints (physiological or other knowledge)**.The pre- and fine- positioning modules have been used successfully with all models imported, highlighting the versatility of the approach.

*Positioning using the contour tool.* This feature is located in the contour tool. It includes a kinematic model for the change of skeletal posture that can be driven interactively by adjusting joint angles or by changing landmark positions from the pre-positioning module (Figure 19). Then the **model transformation is performed by contours** using the same methodology as for the scaling using contours.

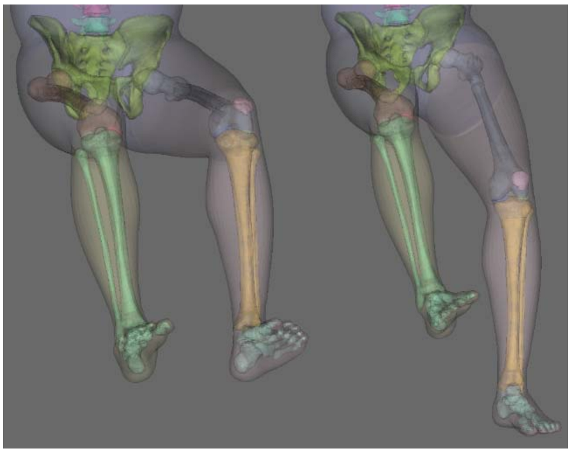


Figure 19: GHBMC M50-O knee flexion in the positioning with contour module.

*Export for positioning by FE simulation.* This feature was implemented using python scripts that can be called directly from within the pre-positioning module. The idea is to export a valid input for an FE simulation where all boundary conditions are already defined to pull the bones of the FE model towards the target position defined in the pre-positioning module (Figure 20). The pulling is made through different strategies using beams, imposed displacement etc. that can be adjusted by the user (three scripts are provided). The python scripts were developed by a PhD in mechanical engineering at UCBL and integrated by INRIA (in particular to be able to save intermediate positions automatically in the process), illustrating the possibility for non-programmers to expand the framework. This **approach allows combining the current positioning practice in the field with the information provided by the PIPER framework**.

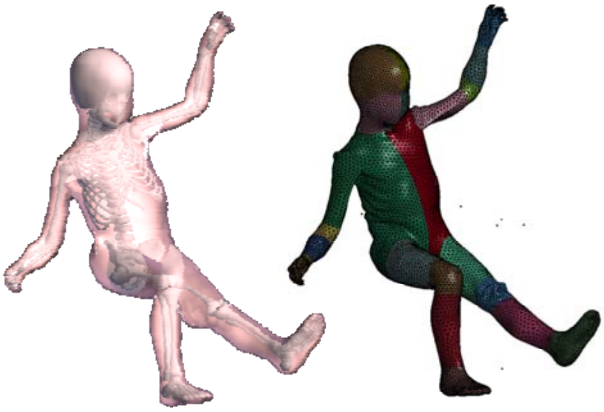


Figure 20: Child model in the PIPER *pre-position* module (left) and same posture obtained by simulation with the Ls-Dyna solver (right) using PIPER FE input export feature.

*Post-processing: mesh and transformation smoothing.* The HBM transformation can result in degraded element quality including severe mesh distortions such as negative volumes, thus preventing the simulation. This degradation can be **inherent to the combination of HBM design and the definition of the target** (e.g. large changes of dimensions or large range of motion) and can in some cases only be solved by remeshing (which was out of the scope of PIPER). For other cases, **smoothing methods were implemented** to try to increase as much as possible the element quality resulting from the transformation to ensure a runnable model after transformation. They include:

- Mesh smoothing using the Mesquite open source library,
- Detection of common surface defects (e.g. after pre-positioning) and surface smoothing (Taubin algorithm)
- Transformation smoothing: assuming that the mesh quality of the original model is acceptable, local defects could be avoided by smoothing the transformation between the source and target model while preventing the creation of penetrations. Two options are provided: smooth by kriging interpolation (with nugget, skin and/or bones as target and a moving box strategy). The functionality was found to be efficient in numerous test cases (e.g. Figure 21). A publication is under preparation. An experimental function to smooth by moving average was also recently introduced.

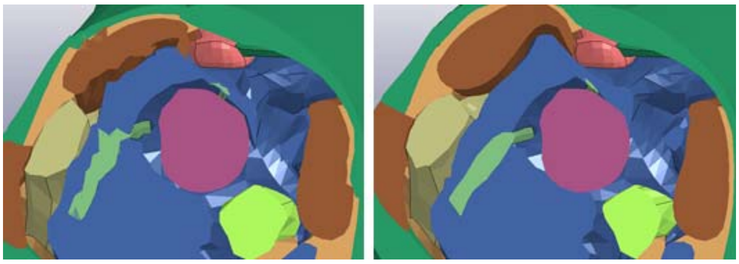


Figure 21: Example of a GHBMC M50-O shoulder transformation smoothing. Left: jagged internal surfaces before smoothing. Right: smooth internal surfaces

*Parameter transformation.* This module allows changing numerical parameters included in the model that are not necessarily related to the node coordinates (e.g. material parameter, part number, element thickness). Using this module, values can be defined in the metadata and updated by the application. The parameters are also accessible through the Python interface. This functionality (which is only used for now by the child scaling module) is expected to be useful to **change parameters that could be correlated to global information present in the target** (e.g. material properties affected by age, thickness affected by stature, neutral zone of a nonlinear beam affected by the posture…).

*Child Model specific module.* A module is dedicated to the scaling of the PIPER scalable child model as a function of age / stature. The module is described in the child modelling section.

*Shape module (experimental).* A shape module to morph the skin and underlying flesh based on lightweight physics simulation was added to provide **another option to deform directly the soft tissue geometry**. It requires a few minutes for its initialization (to build the simulation model) and it is then interactive, a bit similar to a sculpting approach. It has undergone limited testing for now and is labelled as beta/experimental.

## 3.4 Other modules and data not fully integrated in the framework

The functionalities listed up to now are fully integrated in the PIPER application v1.0.0 and directly accessible by the user. A number of other functionalities were developed but not integrated due to limited testing or the lack of sufficient *a priori* data to support them. All of these were delivered under the same open source licenses such that they can be integrated in the future. The main ones are:

- The Statistical Shape Modelling (SSM) software toolbox provides the **ability to generate Statistical Shape Models from registered meshes**, correlate their main modes with global predictors and link them to anthropometric measurements (including accounting for posture). While the tests with the toolbox were successful, the data (meshes) needed to support the work at the full body level were not sufficient. To build that functionality, meshes were segmented from full body CT-scans provided by CEESAR (not collected as part of PIPER) using a reference full body geometrical model. However, despite the efforts, their number was insufficient for statistical modelling at the full body level. All segmentations and the reference model were nevertheless delivered.
- A statistical modelling approach using landmarks was developed as an alternative solution to SSM. The approach uses similar concepts as the SSM but is based on a database of landmarks defined on full body CT scans of 23 subjects (including the reference model). Combined with a direct kinematic toolbox, it was tested for skeletal scaling. It remains an experimental feature (Figure 22) which is not integrated but both codes and landmark database are released.

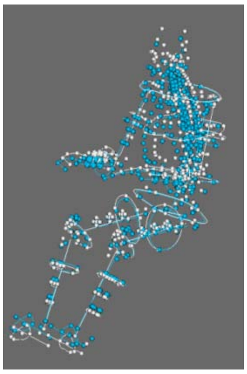


Figure 22: experimental scaling based on landmarks and anthropometry. Landmarks (from a landmark database released by PIPER) can be combined with anthropometric measurements and positioned over a HBM to change both skeleton and external surface.

## 3.5 Safety applications

While testing was performed all along the development both by developers (WP3-WP2) and users (WP1), it was important for the project to **evaluate the software more in depth in realistic and safety relevant application**s. Applications were adapted for their relevance during the course of the project. In particular, pedestrian simulation (which is the only simulation currently introduced in consumer testing) and dimensional changes (in relation with the new regulation R129) were added. Applications were both run by industrial partners (related to the French and German car manufacturers) and academic partners. In the end, applications included:

- *Pedestrian simulation with the GHBMC M50 pedestrian simplified*: the HBM was scaled to evaluate the effect of a stature change on the response. After creating the metadata required for the model import, the dimensions of a PMHS used in the reference test were complemented using the *Anthropometric Prediction module.* The refined target was then adjusted in the *Scaling Constraint* module and the model deformed in the *Kriging module*. After export, the model could be run without error. The results of the simulations suggest that while limited, the stature change affects the timing of impact and some of the kinematic parameters (Figure 23).
- *Pre-crash emergency manoeuvres with the Thums AM40 v4.02*: the HBM was positioned to evaluate the effects of Automatic Emergency Braking (AEB) and Lane Change (LC) on the crash injury parameters. After creating the metadata required for the model import, the model was positioned using the *pre-* and *fine- positioning* modules, followed by the *transformation smoothing* module. The target was specified in terms of landmark positions measured in actual volunteer test in a previous project (OM4IS). Three positions were achieved (normal, AEB and LC) and the crash simulation run. A realistic environment model (with airbag) was developed for this objective (delivered). The results of these specific simulations show that while the injury metrics are widely reduced by the AEB (despite the more forward position), the LC could result in issues due to the more limited airbag engagement resulting from the pre-crash motion (Figure 24). The positioning in the normal scenario was also reproduced with the GHBMC M50-O model and PIPER.
- *Accident reconstructions using the PIPER child model:* four physical accident reconstructions performed as part of the CASPER (2008-2012) EC project were simulated using the PIPER Child model and the PIPER application. The PIPER application was used, in particular, to adjust both stature and position of the child using the *Child scaling*, *Pre-position* and *Transformation smoothing* modules. The reconstructions were conducted on a *parametric vehicle environment* developed during PIPER (and released) and generic child restraint systems developed during CASPER and that the owner agreed to release under Open Source for PIPER. This application demonstrated the feasibility of the approach (see Figure 25), opening the way for the development of simulation based risk curve for the child model. It was also useful to test the stability of the PIPER child model in more realistic environments.
- Other scaling applications (Figure 26) included the development of a workflow to adjust the anthropometry of the PIPER child model to match some of the dimensional specifications listed in the regulation R129 and that cannot be assessed with dummies (using the *Anthropometric*, *Scaling Constraint*, and *Kriging* modules), the scaling (both internal and external) of the PIPER child model to match the weight of PMHS tested in a literature study. A similar application was also performed for the GHBMC model.

Most of these applications are detailed in online tutorials available on the project wiki.

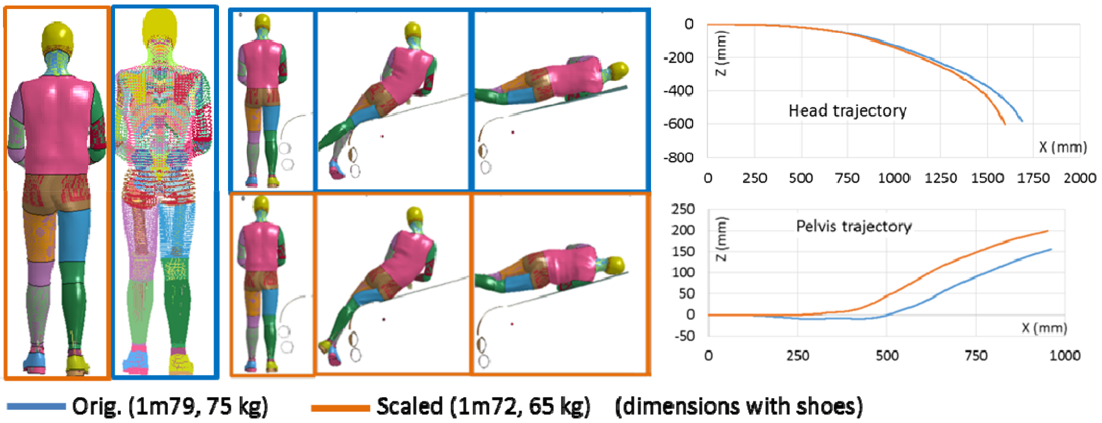


Figure 23: Application with the GHBMC M50 Pedestrian Simplified: the change of stature (using PIPER) led to changes of head and pelvis trajectories as well as impact time.

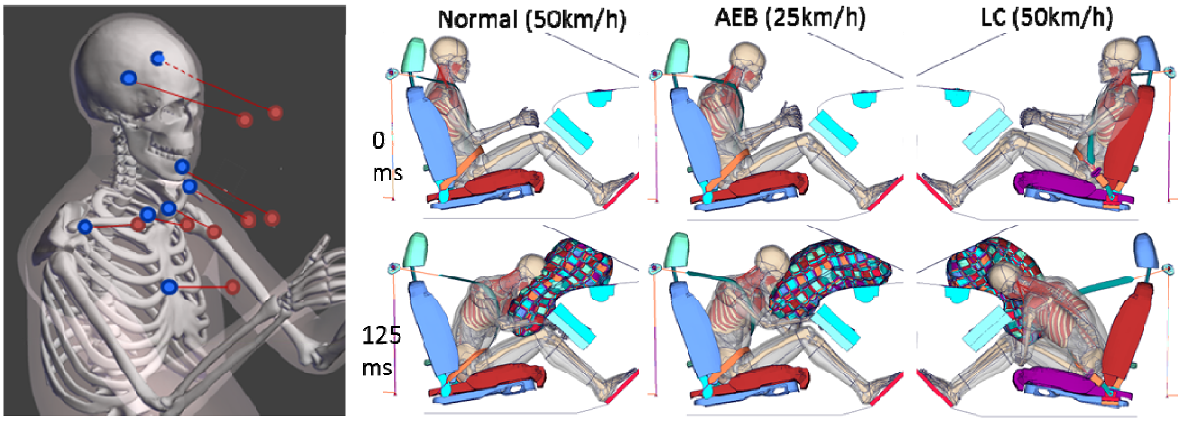


Figure 24: Application with the Thums AM50 v4.02: the change of posture (in PIPER, left, using landmark positions) due to emergency manoeuvres resulted in reduced injury metrics for the Automatic Emergency Braking (AEB) due to the reduced crash velocity, but degraded the injury metrics for the Lane Change (LC) due to the head partially missing the airbag. The LC simulation is shown from the right side to allow visualizing the head impact location.

Figure 25: Application with the PIPER child model and the PIPER parametric vehicle environment model: accident reconstructions were performed using physical reconstructions with dummies as a baseline. The model was first scaled and then positioned in PIPER.

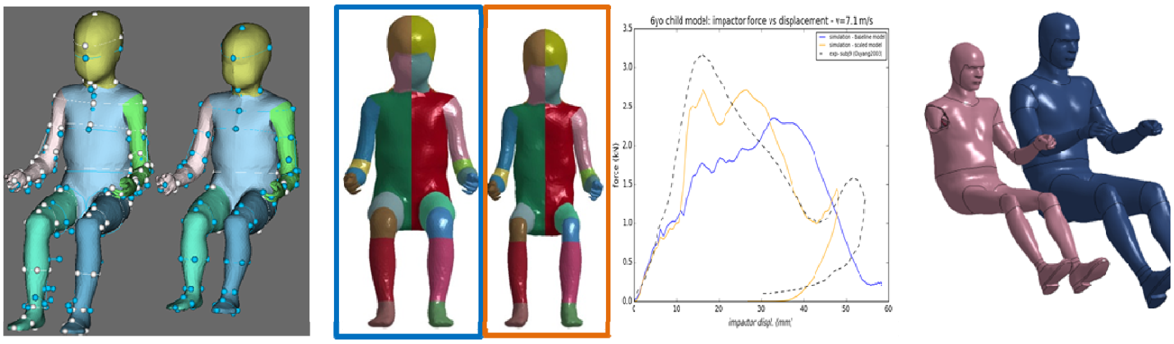


Figure 26: Other examples of scaling with PIPER. Left: generation of a child model with a 95th percentile thigh thickness for a given stature. Centre: the change of weight and stature from 1.13 m, 23 kg for the PIPER child to 1.05 m, 16 kg for a PMHS tested in Ouyang et al. (2003) was found to affect both shape and amplitude of the response in pelvic side impact. Right: GHBMC scaling to match a PMHS anthropometry. These scaling examples all use the *anthropometric*, *scaling constraint* and *kriging* modules (sometimes with independent skin and bone target scaling).

## 3.6 Conclusions

**A new, Open, HBM and FE solver agnostic software framework to position and scale/personalize HBM was developed and released.** It includes **numerous modules** for helping the user to define its transformation target or to transform the model itself. These modules include many state of the art numerical methods, some of which are adapted from different fields (e.g. anthropometric dimensions prediction from ergonomics, computer animation for the pre-positioning module). The framework is extensively documented through its **user manual, tutorials, and through its source code availability. As such, the PIPER framework and application is unique in the field.** A peer reviewed publication process was initiated on many of these aspects. The biggest framework limitations include limited data availability for internal scaling and the limited testing. For the internal scaling, methods were however implemented and could be fully integrated in the future (as they were released under Open Source). For testing, applications conducted by industrial and academic partners demonstrated the usability of the software and models in relevant configurations (pedestrian and occupant, crash and pre-crash, with different models including PIPER child in accident reconstruction, for both scaling and positioning). However, considering the number of options and features implemented, broader testing by a wider community will be required to further evaluate the performance of the software and refine the needs for further improvements. With the recent public release, we are already aware of external users starting to use the software.

# 4. Potential impact and main dissemination activities and exploitation results

Considering the objectives of the project, the **dissemination and exploitation strategies were essential**. From the very beginning, it was felt that the potential impact of the HBM in safety was not fully achieved due to the lack of tools facilitating their use and due to a fragmentation that is incompatible with current business models. Also the lack of openness or standardization seemed especially problematic when aiming for reproducibility, which is essential both for the scientific approach and for any evaluation (whether it is consumer testing or regulation). This vision was reinforced and refined during the project, including through interactions with many stakeholders. The project and its approach were presented at many forums among the most relevant for the field and were always received with interest. These included:

- The Stapp and the Ircobi conferences, which are the two primary conferences in the field of impact biomechanics, as well as a NHTSA workshop
- The Conference on the Protection of Children in Cars, which is the primary conference dedicated for child road safety
- An advisory board meeting with various stakeholders before making final development choices
- The GHBMC and THUMS communities, through close links with the GHBMC consortium (regular progress reports and participation to the GHBMC User's workshop), and links to the Thums User Community (TUC) though PDB.

Private meetings were also held with specific stakeholder including FE solver makers, OEM, other projects (e.g. ViVA, CoHerent), etc. Potential users were also contacted for feedback in the user poll on specifications and in the beta testing phase.

**The cornerstone of the PIPER dissemination approach was to be Open** (as in Open Source and Open Data) and to try to be inclusive (accept all practices, do not discriminate). The need for Open Source was **not a moral position but as a tool to achieve some of the goals of the project**. Great attention was paid to the selection of the licenses, and it took a lot longer than the 6 months originally planned in the Consortium agreement to select licenses for the main results. This time was necessary to try to understand the diversity of Open Source licenses and how the choice could impact the use of the results (risks and opportunities). **The difficulty was to try to balance the risks of forking into incompatible versions (fragmentation), the risk of capture by an entity (whether a project partner or an external private entity such as a solver maker), the risk of HBM or products contamination by the license, and the need to use standard licenses to be understandable and to achieve robust legal standards.** For the child model in particular, despite a significant effort to draft a custom agreement with legal services, the initial vision to have an interim period turned out to be too complex to implement legally (need for consortium, etc). In the end, it was decided to resort to the use of a standard license (with a couple of additional clauses) and to release the child model earlier than initially planned. The following decisions were agreed upon and already implemented as the main results are now already distributed under these open source licenses (the full terms should be checked of course):

- **For software: the general rule is to use the GPL** (General Public License). The GPL forces users to use the same license for all code distributed with a modified version. It does not allow linking to the software. This approach was selected to prevent capture by commercial software companies (e.g. using libraries but not contributing back) and because, as the PIPER software could be the first of its kind, it was hoped it could attract module contributors that could benefit from the framework. It was considered that there was no risk of contamination as long as the software was standalone, and that the risk of forking was relatively low considering the user base. The GPL version 2 or later was selected for compatibility reasons with other libraries. The fact that the Linux kernel, used in most companies that are potential users, also uses the GPL v2, is hoped to reassure legal services.
- **For datasets (e.g. used in scaling), the Creative Commons CC-BY-4.0 license was selected** as the rule, as a risk of HBM contamination was identified for stronger licenses that would put conditions on the derivatives. This license requires citing the authors but only has very little requirements on the derivatives. It is used for most datasets (databases, segmentations, etc).
- **For specific parts of the software (interfaces, etc.), a more liberal license allowing re-use or linking in commercial software** was adopted to facilitate communication between models or software. Examples are AnatomyDB using the LGPL v2.1 and CC-BY-4.0 licenses (for the software and data, respectively) to promote common vocabulary in the field. This is also the case of some of the templates defining the PIPER file formats for example.
- **The PIPER child model was release publicly at the end of the project under the terms of the GNU General Public License version 3 with additional clauses**. As this license, which is more recent than the GPLv2, explicitly allows adding some clauses, an Open Science clause (asking for release if the model is used in scientific claims) and a liability clause (similar to the one of the ViVA

model) were added. It is believed that the Open Science clause could be helpful to limit the risk of forking and mixing with research models that would only be used in publications but not distributed to the community. The validation setups of the child model were released under CC-BY-4.0 to promote re-use and comparisons with other models without risking contaminating them.
- **For the car environments; the GNU General Public License version 3 with a liability clause was used** (no open science clause).

**All selected licenses allow business as a service and do not discriminate between types of users (e.g. academic or industrial).** This means that small companies with sufficient knowledge could start providing services to larger companies, or that the results could be used for teaching and research (e.g. the combination of PIPER framework, PIPER Child model, PIPER Generic Car environment and Generic Child restraint system released VFSB could provide a very useful combination for teaching).

Regarding forking, it was realized that it would be difficult to prevent users from forking the software or model if they really wanted to as the need to be able to fork is essential to prevent the capture. Instead, **it was decided to deal with the risk of problematic forking (the one that would lead to fragmentation) by explaining the associated issues and try to convince the community** of the detriments of fragmentation and the benefit to all contribute to the same versions.

One special type of result generated during the project was the **metadata files** allowing to import the HBM into the PIPER framework. As these may include IP of the HBM they were developed for, **discussions are still ongoing with the GHBMC and Thums developers** and distributors to find the best way to distribute them to the users. If they agree, the metadata files will be released under a CC-BY-4.0 license.

**Open Source animation: www.piper-project.org**
The message on forking was promoted in contacts with stakeholders and was overall well received. The positive feedback received in dissemination efforts also suggested that it may be possible to quickly create a user community around PIPER. It also appeared that **a structure was needed to continue promote the PIPER vision** and animate this possible community beyond the end date of the EU project. This structure would also be helpful to encourage and consolidate the contributions, try to coordinate the efforts, animate the community and provide some help. After discussions in the project, it was decided to **initiate and Open Source effort (www.piper-project.org)** following the EU-funded project. Its general principles were agreed upon at the last general assembly of the project. The Open Source project was announced at the final workshop, along with the following information:

*Vision.* The project aims to promote the use of human body models to improve transportation safety:
- By developing and making widely available tools facilitating their use and their reproducibility
- By increasing their ease of use, making available missing tools/models (e.g. child)
- By encouraging contributions for the emergence of common practices, maintenance solutions and evolutions through an academic and industrial users community
- By helping to harmonize practices though openness

*Core values* are:
- Open Science and Open Source, as a mean to secure access (without time limitation) to tools needed to improve safety and to share the required efforts (no need to develop your own)
- Trying to be inclusive and account for existing models, codes and practices (model, code/vendor agnostic solution)

*Guidelines for contributions* are:
- Software: test and review the code (must respect vision of framework, programming guidelines etc.). Modular structure can help (python scripting, etc.)
- Child model: validation cases are provided. The reason for each proposed change must be explained and validation cases rerun to check global effect…
- Metadata: ensure that there is no private IP in what is released

*Organization and composition*: the project is for now an ad-hoc group with a decision making process composed of:
- Board: Its role is to work on the vision, strategy, roadmap and communication (Communicate, educate, encourage, animate, coordinate to reduce the chances of takeover/forking, steer towards roadmap/vision, Enforce license, Organize support, recognize in kind contributions…)
- Technical groups: Decide to accept contributions, Create authoritative source / versions ("quality label"), Animate discussion
- The composition is open with rules. The current composition is mostly people from most PIPER partners for now but others can join.

  - To join: they need to share vision and values, contribute something (significant), everyone needs to agree with (co-optation), people not organizations, need to be practically involved, need to respect code of conduct.
  - Required qualities: prominent participants that would help promote, organize, contribute (not there to promote a hidden agenda…), have relevant knowledge and (some) time available…

Regarding communication and support, the main objectives for now will be to maintain the code repository (merge contributions, etc.), manage info, label versions, etc. It is expected that there will be at least one yearly user meeting. Regarding the support, the amount will depend on the funding source and volume, as well as the good will from the participants to answer other's questions. The PIPER project partners have some permanent staff helping for the transition but there is no funding secured for maintenance for now. It is also hoped that commercial support can be started by some parties (it is not the role of the open source project). Technical expertise is available, including for paid support and development tasks (e.g. CEESAR for support/training & light development, Anatoscope (start-up composed of former INRIA staff) for heavy development).

**Ongoing initiatives**

**Several actions were initiated at the end of PIPER by the PIPER partners or by third parties**. They include:

- A proposal was written for an H2020 call with part of the PIPER partners and others. However the proposal was not selected.
- PDB organized an evaluation of the PIPER child model (including by a third party) and announced at the final project workshop its intention to position the Child model for use as a pedestrian model and to convert it to the Pamcrash and Abaqus solvers. These models would of course be Open Source.
- Activities related to PIPER were initiated by some PIPER partners beyond the PIPER Description of work. This includes a PhD thesis at UCBL funded by LAB, and activities on infant modelling at KTH
- Third parties (including a US university) applied and secured some funding for work using the PIPER Child model
- A short PIPER session is being prepared for a human modelling conference at the end of the year (upon invitation of the organizer).
- Some users (from both academia and industry) have started evaluating the PIPER software and Child model (based on email questions) distributed at the workshop.

**A call for contributions all of types (collaboration, funding, development) was made** at the final workshop (also available on Youtube). While some contacts are already ongoing, we believe that users need some time to use the software and child models (that were just released) before moving further.

Overall, we feel that the PIPER results have attracted a considerable interest from a community that is receptive to the main goals of the project. The effort will continue to further develop this interest. This is true for both software and child model (which was particularly well received due to the lack of widely open option in the community).

# 5. Address of project public website and relevant contact details

EU Project web site: www.piper-project.eu

The PIPER Open source initiative which follows the EU project is available on www.piper-project.org