A public-private integrated framework for in-silico virtual testing: the open-source PIPER project to personalize and position HBMs

Bertrand Frechede, Erwan Jolivet, Christophe Lecomte, Thomas Lemaire, Philippe Petit, Philippe Beillas

A public-private integrated framework for in-silico virtual testing: the open-source PIPER project to personalize and position HBMs

Bertrand Fréchède[1], Erwan Jolivet[2], Christophe Lecomte[3], Thomas Lemaire[4], Philippe Petit[5], Philippe Beillas[1,*]

[1]LBMC UMR_T9406, Univ Lyon, Université Claude Bernard Lyon 1, IFSTTAR, Lyon, France,
[2]CEESAR – European center of studies and risk analysis, France
[3]CED Group, Faculty of Engineering and the Environment, University of Southampton, UK
[4]Inria, Univ Grenoble Alpes & CNRS (LJK), France
[5]Laboratory of Accidentology, Biomechanics and human behavior, PSA Groupe & Renault, France

* Correspondence: philippe.beillas@ifsttar.fr, +33(0)472142371, 25 Av. François Mitterrand, F-69675 Bron

1. Introduction

As shown by the main topic of the VPH2016 conference, 'Translating VPH to the clinic' is now a critical objective of the VPH research community. At the same time EuroNCAP, the European consumers' association for vehicle safety rating, very recently introduced the use of Human Body Models (HBM) simulations to define some of the test conditions in their consumer test protocols for pedestrian impact scenarios. Although they may at first seem somewhat unrelated, such different research areas as the clinical and automotive crashworthiness research benefit from the same advances in numerical methods and computational capacity for imaging and modelling. Further, both research communities may share very similar challenges, not only in their approach to the modelling of the biomechanical behaviour of the human body, but also in their need to transfer this research into tools that will effectively prove their societal benefits in a safety and regulation constrained socio-economic environment. With relatively similar aims and scopes, expectations in the field of *in-silico clinical trials*, or *virtual testing*, are high in both industries.

The PIPER project is a 3.5 year EC funded research project that aims to deliver tools that will allow a user to personalise and position any Finite Element (FE) HBM, in a virtual vehicle environment, for virtual testing. The challenge is scientific, as state-of-the art methods had to be designed and implemented to e.g. develop Statistical Body Shape Models (SSM) from clinical imaging data, or to ensure that deformed FE models would still meet solvers' quality metrics for simulations. The promotion of such tools was identified as critical and strong choices (open-source, meta-tools – independent from the FE model/code, contribution of the end-users to all stages of the project) were made to ensure a successful public-private research partnership. This abstract presents some of these key aspects, with an emphasis on their possible usefulness and transfer to the VPH community.

2. Materials and Methods

In the automotive application context that is presented here, personalizing an existing FE HBM model means scaling and deforming it towards dimensional and shape targets. Positioning a FE HBM model means being able to reposition its segments towards a target posture. The THUMS[1] or GHBMC[2] models are state of the art examples of such FE HBMs for crash applications. While very detailed, they correspond to a limited set of specific subjects' dimensions, properties and to limited

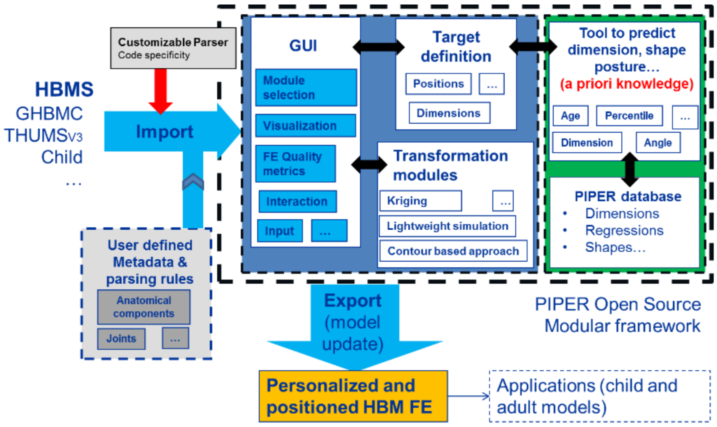

Figure 1: The PIPER workflow

[1] http://www.lstc.com/thums
[2] http://www.ghbmc.com/

postures. Two main complementary software components form the core of the PIPER tools (Cf. Figure 1): first, the statistical predictor tools provide a description of body shape and/or position from few user inputs (age, height, positional constraints…) and a-priori knowledge regarding physiology, biomechanics and ergonomics. This a-priori knowledge was acquired from either the literature, existing datasets, or from newly generated information. Merging information from various datasets to generate a statistical model of the whole body is the main scientific challenge for this task. The second software component is composed of personalizing and positioning modules that rely on a range of near real time geometry- and physics-based numerical methods, to transform the FE HBM towards targets that describe the desired position or body shape determined by the user and the first component. The challenges are to combine these constraints of targets and user inputs with the functional constraints of FE HBMs (contacts, kinematics joints…) and to ensure that FE quality metrics are met to permit the FE simulation.

Statistical predictor tool (a-priori knowledge) Several anthropometric measurement databases are available for a wide range of populations (e.g. ANSUR, NHANES, …) and regressions of anthropometric measurements were generated using previously published methods [1]. Mean or sampled anthropometric measurements for specific subjects (a given BMI, age, etc.) from a chosen population can therefore be predicted and used to define the target dimensions for personalization tools. However, these targets mainly define the external body shape. The internal geometry is based on a statistical model of the whole skeleton built upon a SSM approach. In order to build SSMs, a set of population samples geometries, e.g. as result of 3D imaging techniques, has to be gathered and a reference mesh needs to be defined and registered on the population samples to perform the statistical analysis. Publicly available segmented data for full bodies is however limited, and segmentation or model based registration usually requires much manual work using a dedicated software. The AnatoReg software is a semi-automated registration solution that was developed by the Anatoscope[3] company, a spinoff from our INRIA partner, during the project. It is based on advanced interactive model-based registration algorithms used to generate a subject's geometry from a whole body CTscan. Based on sampled landmarks or surfaces meshes evaluated on subjects, the variability of shapes, in particular those of the skeletons, was then expressed in terms of SSMs. As shapes of bones are independent of posture, their SSMs were evaluated through bone by bone partial Procrustes analysis [2], before analysing the mean, variance, and covariance of the whole skeleton shape. The shape SSMs can provide surface mesh targets either from the shape means or from sampled virtual subjects. Providing the statistical description of the whole body will finally be addressed by linking the above presented anthropometric measurement databases, which are available for a much wider range of populations, to the surface shapes.

Regarding positioning, defining predictors can have many advantages for the user where a physiologically likely position is needed but would be either unknown or too tedious to define by hand. An example concerns the predictive positioning of the spine where a-priori knowledge is provided by the combination of different methods. An inverse kinematics articulated linkage model of the skeleton [3] forms the backbone to the predictive positioning tool, allowing to solve for a user-defined target body posture under constraint of e.g. vehicle environment. Postural task-related linear regressions were then calculated on a set of parameters defining a 3D spline based on both *in-vitro* and *in-vivo* bending data to refine the postural prediction of the spinal segment. Thus in the positioning step, e.g. the pelvis and head position and orientation may be used as input to the spine predictor. The predicted output spline will then be used to constrain the position of the articulated vertebra of the PIPER model, by minimizing the distance between the model's vertebras and their counterpart positions on the spline.

Personalizing and positioning tools In order to apply the above defined predicted targets (shape and/or position) on any FE HBM regardless of its FE format, a customizable FE parser was implemented to describe specific FE format rules to interpret the model into a custom PIPER format. A set of metadata (defined only once by the user, for a given FE model) is also required to describe the anatomy of the FE HBM and its functional constraints. From the model geometry and its metadata, a simplified physics model is built, composed of bones and the flesh. The bones are articulated from the robotic joints defined either in the metadata or from anatomical landmarks pointed on the HBM in the metadata. Joints may also be defined using a combination of sliding contacts and generalized spring between bones to achieve more complex kinematics. Once imported, the user can interactively define say positional constraints using a real time light-weight physics simulation. The physics model accounts for bone collisions so that

[3] www.anatoscope.com

the range of motion of the HBM respects its bone geometry. The flesh is simulated as a uniform material using a frame based approach developed in the computer graphics community [4]. The resulting system of equations, comprising the physics material law, the joints and contacts constraints as well as the user-defined positioning targets, is efficiently solved using a mixed stiffness/constraints approach [5] implemented in the Sofa simulation framework[4]. This simulation respects the main functional constraints defined in the FE HBM. To obtain a realistic target position, the ergonomic and biomechanical constraints defined by the predictor tools will then be considered in the simulation as soft constraints. The same approach is offered to the user regarding the personalization to combine model requirements and statistical predictions of shapes.
To finally transform the FE model towards thus defined targets, a set of numerical methods have been implemented following a benchmark study regarding their performance with regard to the precision of the transformation, the impact of the transformation on mesh quality and the respect of FE functional constraints (i.e. the model can be run in a FE simulation) [6]. Regarding personalization, the dual Kriging interpolation was implemented as it was shown that in such application the key factor is how the target is defined rather than the interpolation scheme. For positioning, two different approaches were implemented. The first one is a more precise version of the above mentioned physics simulation, which computes a deformation field in the whole space. The second one is a contour-based geometrical approach that uses specific metadata to take into account joint specificity [7]. A set of tools were finally implemented to improve the realism of the body shape and the FE mesh quality after a transformation.

3. Results

Statistical predictor tool (a-priori knowledge) The AnatoReg tool has so far permitted the prototypical semi-automatic segmentation of the thorax and lower limb bones of 25 Post-Mortem Human Subjects (PMHS), with a user-time of roughly an hour per subject. Skeletons of over one hundred PMHS whole body CTScans are planned to be segmented; these models as well as the manually segmented reference models will be made publicly available. The data will include both surface meshes and an extended set of anatomical and anthropometric data used to identify joint coordinate systems and articulate the skeleton.
The developed a-priori anthropometric tools based on [1] first permit to generate virtual populations and then to evaluate regression models between any chosen predictors and measurements of interest. For example, from the ANSUR data [8], one can generate a virtual population with a given male-female ratio, generate the regressions between the BMI and stature predictors on one hand and external body measurements on the other hand. Shoulder breadth and thigh circumference can then for example be predicted for subjects having a stature of 1.65 m and a BMI of 23. Tools to generate the SSMs can be applied to all the parts of the segmented body (the skeleton at this stage) or to part of it. One can then predict the mean shapes or sample some of them, while considering correlation between them. For example, one can sample whole sets of vertebrae such that the dimensions of all of them are consistent. Another possible use of the SSMs is to calibrate their modal weights to match as closely as possible a specific subject. Regarding the positioning, a first version of the inverse kinematics tool and spine posture predictor have been implemented to predict a-priori postures in the sagittal plane.

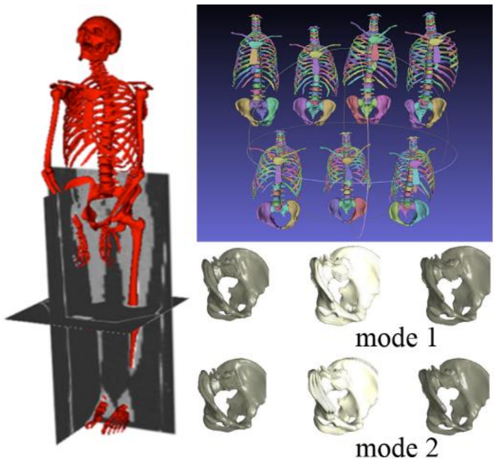

Figure 2: AnatoReg model based registration examples; pelvis SSM first two modes with ± 2.0 'sigma' deviation

Personalizing and positioning tools The PIPER model can be interactively manipulated to position the HBM through a dedicated GUI (Cf. Figure 3). Users also have access to many positioning parameters such as joints angular values (ex: hip flexion), bone orientation (ex: pelvis tilt), bone position (ex: head or hand position). Further to the evaluation of the FE model transformation [6], the personalization and positioning workflow have been evaluated on a range of end-user defined application scenarios by quantifying for FE quality metrics after transformation. The link between the statistical predictor tools

[4] www.sofa-framework.org

and personalizing and personalizing is not implemented yet and will be the main milestone for the last year of the project.

4. Discussion and Conclusions

This abstract presented a general framework as well as some key methods and tools that will be delivered for personalizing and positioning FE HBMs at the end of the PIPER project (April 30, 2017). The scope of the project is ambitious on several aspects. On the scientific side, some new developments have been proposed [6, 9] to e.g. answer the need for quality control of geometric deformation and quick and efficient automatic model registration. On the project design and management side, the requirement of transferring tools to the industry resulted in implementing some novel approaches to involve both public and private partners (and thus, the end-user) at all stages of an EC funded project. This included a questionnaire to users, case-study application scenarios, versioning of tools' deliverables and users' beta-testing. Strong design choices were made by imposing a fully open-source framework for all tools and databases to be released and by aiming at a meta-tool, i.e. not FE model/code dependent. An open-source design meant a strong change in cultural paradigm for our industrial partners, but also proved an incentive to federate new contributions to the project and aimed at ensuring that a users' community will continue to build up and feed the tool and its databases after final delivery.

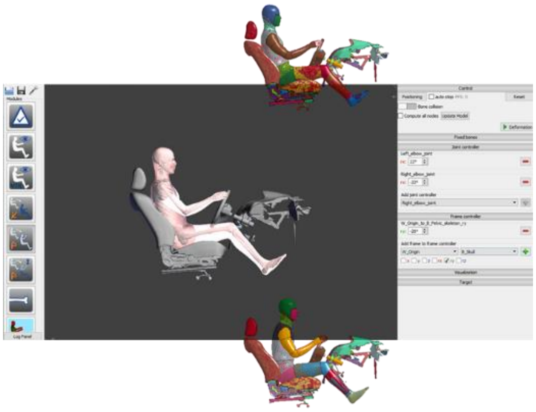

Figure 3: PIPER GUI with an example of FE model before and after positioning

The applications presented in this abstract target the automotive industry. However it is to be strongly emphasized that the PIPER tools are by design not restricted to be used in this field of application. Some of them, like SSM or Kriging/RBF approaches were already used or even initiated by the VPH community for clinical applications. Some, such as the anthropometry tool and database, may be of interest to different publics, and will be released as fully standalone options or separate software. The AnatoReg software allows for quick personalized surface model building and registration from medical imaging and the a-priori knowledge toolbox may be used to account for subjects' variability when designing parametric studies or sensitive analysis for numerical verification [10]. « Accurate models produce predictions that are consistent with the experimental observations under a wide range of conditions » [11] and being able to model the human's physiological variability appears to be key if we wish to have *in-silico clinical trials* accepted by the regulatory experts and policy makers. Finally, the personalizing and positioning tools may be used for personalization of existing complex segmental FE models. From the authors' perspective, these tools open new perspectives in a broad range of FE modelling applications and have the potential to significantly facilitate already initiated subject-specific modelling processes in the VPH community.

Acknowledgements This research has received funding from the European Union 7th Framework Programme ([FP7/2007-2013]) under grant agreement 605544 [PIPER, http://piper-project.eu].

5. References

1. Parkinson M et al., International Journal of Industrial Ergonomics. 2010;40:106–111
2. Dryden IL et al. (eds.), *Statistical shape analysis*, John Wiley & Sons New York, 1998; 4
3. Monnier G et al., Proc DHM Conference 2006: SAE Technical Paper 2007-01-2454
4. Gonzales Hidalgo M et al. (eds.), *Deformation models: tracking, animation and applications*, Springer Netherlands. p. 145-166
5. Tournier M et al., Proc SIGGRAPH 2015. ACM Trans Graph. 2015;34(4): paper 132
6. Jolivet E et al., Stapp Car Crash Journal. 2015;59:337-357
7. Jani D et al., Traffic Injury Prevention. 2012;13:640-649
8. Gordon CC et al., *Technical Report*, US Army Natick Research Development and Engineering Center, Natick, MA, 1989; TR-89-044.
9. Moreau B et al., Proc ESB 2016: paper 684
10. Viceconti M et al., Clin Biomech. 2005;20:451-454
11. Viceconti M et al., *Avicenna Roadmap*, Avicenna Alliance. 2016; 119 p