INJURY BIOMECHANICS RESEARCH
Proceedings of the Fortieth International Workshop

Personalization – addressing the anthropometric variety using a human body model.

M. Pedzisz, J. Toczyski, T. Dziewonski, C. Rzymkowski -
Warsaw University of Technology, Poland
P. Baudrit, Centre Européen d'Etudes de Sécurité et d'Analyse des Risques, France
M. Jansova, University of West Bohemia, Czech Republic

ABSTRACT

THOMO reference model - a finite element model of the 50th percentile male based on simplified GHBMC model served as the basis for most of the virtual tests in THOMO project - lateral and frontal Kroell type thorax loading. In order to compare and validate the model's performance with cadaver tests one of the aims of the THOMO project was to develop reliable methodology to modify/scale the reference model geometry to fit global dimension of chosen PMHS and locally adjust the rib cage. Such modification of the reference model is further called personalization. Developed methodology combines global dimension scaling with locally controlled shaping of the rib cage area. Combination of scaling dependencies between separate parts of the body segments and layers together with quite amount of control points established on thorax, basing on CT scans of real cadavers and followed by application of kriging based morphing algorithm, makes the overall process not trivial to handle. Presented methodology introduces backgrounds of applied approach, illustrates main steps of the procedure, as well as geometrical and numerical validation of target models. It is followed by examples of applications the personalized models were used for, like direct validation of experimental signals and the model's output, comparison between global scaling and newly proposed personalization method in terms of model's differences in geometries and performance, etc. As a general result of THOMO project, by using personalization methodology, 6 personalized models (4 representing 50th male cadaver's geometries and 2 resembling 5th small females subjects) have been successfully developed that may serve for any further in-depth analyses.

INTRODUCTION

Current Anthropometric Test Devices have inevitable limitations. Three standard sets of dimensions, used for the testing procedures (5th, 50th and 95th percentile), do not cover the anthropometric variety of the vehicle users' population. Additionally, it is not possible to address the structural or tissue level diversity between the occupants, e.g. related to age. Therefore, a need of application of the human body models arises. To reduce the research and development cost and assure repeatability, the test subjects (volunteers, cadavers, animals) are complemented with the numerical models. The THOMO model is an example of the numerical human body model, with a detailed representation of the thoracic section.

The research was performed within the THOMO project (FP7, www.thomo.eu). The THOMO project interacts with the Global Human Body Model project (www.ghbmc.com), which aim is to obtain and maintain the world's most biofidelic human body models.

At the European level, a complete finite element model of a human being in a sitting position was developed through FP4, FP5 and FP6 projects. The HUMOS model was born in 2000 and then progressively improved during the HUMOS2 and APROSYS projects. However, the use of this validated model is limited. The mesh is coarse and most of internal organs as well as bio-material properties at the tissue level are not included, due to the computing capacities of that time. HUMOS was developed to biofidelically predict the vehicle occupant kinematics, the restraint system loads and a few fracture type injuries. This is not sufficient for the current virtual testing applications and needs. Challenges are known for all the available human FE models: Huang under PAM-CRASH (Huang et al., 1994), Lizee under Radioss (Lizee at al., 1998), Ruan under LS-DYNA (Ruan at al., 2003, 2005), Kimpara under LS-DYNA and PAM-CRASH (Kimpara at al., 2005), Ford model, GM model and LABMAN. These models reflect simplified current knowledge of the human body geometry and injury mechanisms. The following challenges are recognized:

- most of the models are based on the geometry of one single human being,
- the rib cage geometry is not sufficiently studied, even though it influences the fracture location, depending on the load type,
- the soft tissue role is not clearly identified in the global mechanical response,
- the injury mechanisms are not completely determined,
- the interaction model (between the skeleton and the soft tissues and between the organs) is usually chosen by default,
- the base of validation tests often lacks control of the conditions at the limits,
- the validation is limited to the global mechanical values.

The base of validation data is not complete enough to allow users to distinguish the biofidelic models from the non-physical ones. With an incomplete validation database, several models can be considered biofidelic and give conflicting results, particularly internally. Even if, by chance, researchers have some confidence in the validation of the model, extrapolation is very difficult. In fact, a numerical model is particularly interesting in considering new safety solutions, which are not, by definition, in the validation database.

The objective of the research was to show an approach to modify the reference, 50th percentile, model in order to obtain a model, representing a real cadaver in terms of the global geometry and adjusting the rib cage local geometry. The applied method was called personalization. Understanding the advantages and challenges related to this approach allows for a successful development of a new as well as improvement of the existing human body model. Another motivation was to better understand the influence of the individual anthropometry on the mechanical response and injury level.

The purpose of this research was also to evaluate the personalization method and compare the mechanical response of the human body FE model representing a specific cadaver with its reference time-history curves at different loading scenarios. Performing same procedure for six personalized models allows for understanding the challenges and specific points of interest for improvement, both for the personalized but also for the reference FE model.

During the analysis a 50th percentile human body model prepared by GHBMC, and further modified, simplified in some regions to multibody (MB) model, and developed within THOMO project was used. The model contains around 700k structural solid and shell elements forming parts of bones, muscles, and other soft tissues. The neck, head and legs are modelled as a rigid body entities (Figure 1).

Figure 1: FE representation of the THOMO reference model. Combination of bone, flesh, muscle and internal organs structure.

METHODS

Before the personalized models mechanical response analysis could be performed, the actual models need to be generated. The personalization method requires some specific data taken on selected cadavers. A data from cadaver experimental tests are also required to check models reproduction of the reality.

The process of personalization consists of two parts, which are called global and local adaptation of the model's geometry. The methodology used to achieve those models was developed at Warsaw University of Technology during THOMO Project. The approach differs to methods described in the literature (Vezin et al., 2009). Although the focus of this study was thorax area, the modifications were not only subjected to this human body part or its fragments, like i.e. rib cage bones, but to the entire body.

The main application area of this method is occupant finite elements (FE) models with any degree of complexity. The dual-kriging interpolation, primarily developed to work out the topographical maps for gold mining industry, was used for this task. A ready-to-use software (HyperMorph module of Altair's HyperWorks package) was chosen as a geometry morphing tool. The linear drift and covariance parameter of kriging was set to the one intended for 3D cases (Matherton, 1973, Trochu 1993). Simultaneously it was stated that the functions describing the new shape have to be guided through the chosen control points.

The utilized model, as most of FE human body models available on the market, reflects occupant in driver position. It makes preparation of the transformation procedure a little complicated, as no standard anthropometry measurements are taken in such position. Therefore, some additional dimensions had to be recalculated from available data to perform morphing of the geometry. The second problem is the fact that the human body is a continuous structure and cannot be divided into separate parts, as it is possible for dummies, for which scaling is used in development process. Nevertheless, using kriging method such limitation was overpowered.

Global personalization

The global personalization procedure, also called scaling (Pedzisz at al., 2012), is based on modification of selected external anthropometric measurements of the human body (chosen cadavers). The internal segments, i.e. bones, muscles and internal organs are modified proportionally to the deformation of an external contour.

The process begin with preparation of reference full body 50% model. A whole model is treated as one entity, symmetrical with respect to the mid-sagittal plane (lat. planum medianum). This assumption simplifies significantly the procedure itself. Locations of around 140 control points (CPs), origins of the transformation, are set on such a model.

The global personalization parameters are defined as the ratio between the target anthropometric measurements of post-mortem human subjects (PHMS) and the data taken on reference 50th percentile model. The process itself consists of a series of changes applied to the location of certain CPs. Such an approach required definition of relationship between chosen markers in a way to force desired displacement of the global control points when the other ones are modified, and to keep the distances between them at a reasonable level (Figure 2).

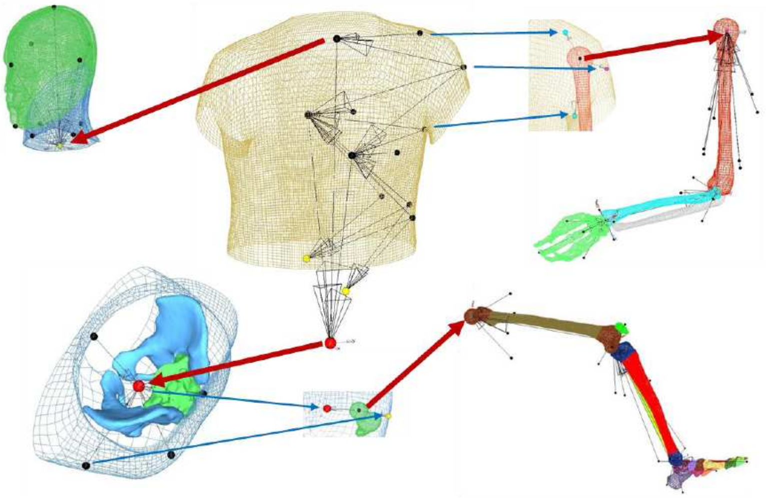

Figure 2: Groups of control points for the external geometry modification, with the dependencies between them shown.

The complete geometry of the body is morphed all-at-once. In the first step, the locations of control points are transformed beginning from limbs and steadily moving in the direction of the trunk. Then the modification of the FE mesh follows.

Local personalization

The thorax local personalization procedure is an extension of the global method, though it is more complicated and time-consuming task. It is a stepwise approach instead of simple global deformation. It also requires in-depth anthropometry data of the subjects, i.e. CT rib cage geometry and µCT data of ribs.

Some of the global control points in thorax and abdomen regions are repositioned with slight adaptation of dependencies between them. Selected parts are "separated" to some degree from the rest of the model. Each rib, sternum, costal cartilage and each vertebrae are treated as local structures modified based on their own set of CPs. This step helps with rib cage adjustment to real specimen. Additionally, the mesh of intercostal muscles is detached from the rib cage geometry. It is also removed from global deformation stage to modify its shape independently. It is an effect of some problems encountered with mesh correctness. To ensure appropriate deformation of the chest, a set of carefully selected, corresponding to data taken from CT geometry of the subjects, local CPs is defined (Figure 3 and 4). The selection of points on the real geometry was done for all 6 chosen subjects. Each of rib cage parts got its own group of them, so the final number of points of influence increased to over 750.

Figure 3: Control points (yellow dots) defined on the model geometry.

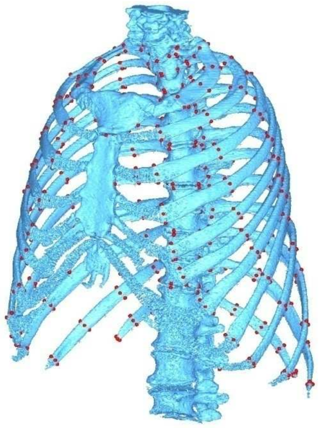

Figure 4: Exemplary geometry derived from CT scans with selected control points on in (red dots).

The personalization process is a combination of scaling and shifting of control points. Though the global part is the same as previously described, the local one, connected with rib cage geometry, is a stepwise approach. Based on the data taken from the model and CT geometries, the shift for all local CPs is calculated. It is worth mentioning, that a simplification was made at the stage of PHMS data preparation. The geometrical data was symmetrised to correspond to the global method. However, due to high deformation of geometries of different subjects, for instance high scoliosis, differences in ribs height, rib cage distortion, which could be connected with PHMS body position for CT scan procedure, such assumption was made.

A generation of locally personalized model starts from the whole body and rib cage internal geometry and topology modification, adjusting the internal organs proportionally, and then adjusting of the intercostal muscles (Figure 5).

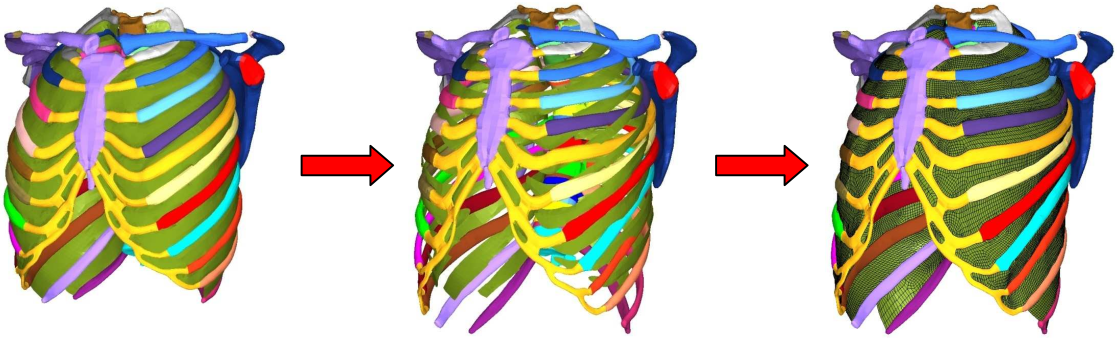

Figure 5: Thorax geometry personalization steps.

The main drawback of the method is a final check and tuning of the obtained mesh, to correct issues resulting from mixed global (external geometry) and local (internal geometry, change of topology) kriging approach. Additionally, the increase in control points number significantly increases computation time of the process.

There is also no CPs on the internal organs, which are modified based on resultant effects of both types of mesh deformations during the process. This however might be recognized as one of the limitations of the method.

Due to the selection of the reference model, which is built as a connection of structural FE and multibody methods, the final mass of the models was checked and improved if needed. The rib's cortical bone thickness map modifications were also performed according to data derived from µCT scans of modelled subjects.

Model's loading conditions

The method was applied to the reference 50th percentile model to generate four male personalized models and two small female personalized models. Further these models were checked in simulations in frontal, lateral and oblique impacts (Kroell et al., 1971, 1974) - Figures 6, 7 and 8. The results were compared with the mechanical response of the cadavers and the biomechanical corridors for the given test conditions. All the mechanical tests were performed within the THOMO project. Software used during simulations was LS-DYNA.

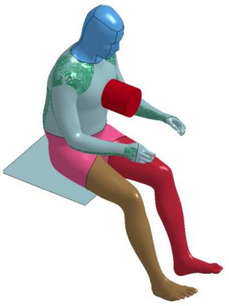

Figure 6: Frontal test setup.

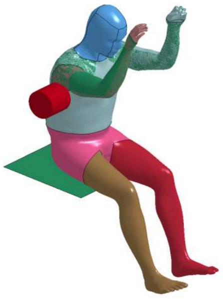

Figure 7: Lateral test setup.

Figure 8: Oblique test setup.

RESULTS

As a direct result set of 6 personalized models have been developed – 4 corresponding to 50th male geometries and 2 corresponding to 5th small females. The method chosen for personalization gave promising results, regarding the geometrical accuracy. Apart from visual comparison, a set of carefully chosen quantities based on specific geometrical measurements have been used as indicators of target geometrical correctness /UVHC – THOMO internal reports/. An example (Figure 9) of the cadaver geometry from the CT scan (yellow) and the corresponding FE model (blue) shows some differences resulting from the assumption of rib cage input data symmetry to morphing process. Nevertheless, the overall agreement is very good.

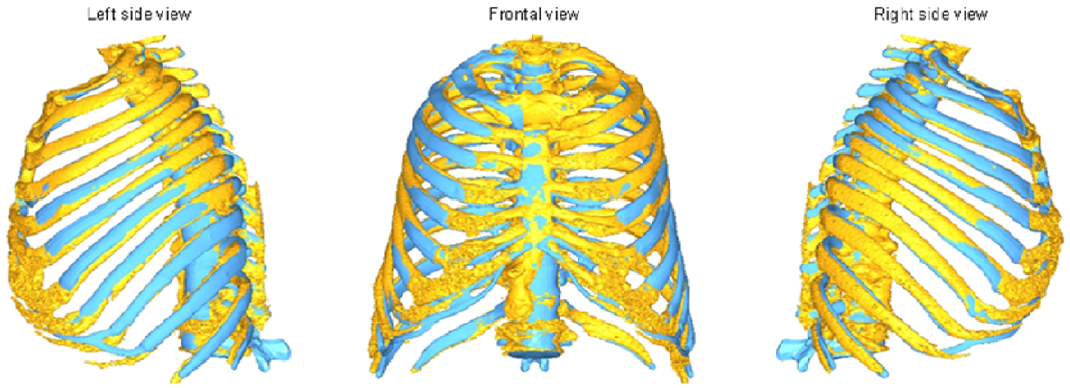

Figure 9: Exemplary thorax geometry comparison - model (blue) vs. CT scan (yellow)

Derived personalized methodology aimed also to reach new geometrical state without drop in model mesh quality. The tables (1 and 2) presented below shows exemplary results of slight numerical quality change between reference and personalized models. As a reference standard set of element quality quantifiers and their corresponding thresholds have been used. They are:

- Jacobian – a measure of the deviation of an element from an ideally shaped element
- Warpage – the amount by which an element or element face (in the case of solid elements) deviates from being planar

- Skew
  - for trias it is calculated by finding the minimum angle between the vector from each node to the opposing mid-side and the vector between the two adjacent mid-sides at each node of the element
  - for quads it is calculated by finding the minimum angle between two lines joining opposite mid-sides of the element
  - the check is performed in the same fashion on all faces of three-dimensional elements
- Aspect – the ratio of the longest edge of an element to its shortest edge

Table 1. Numerical quality of reference model thorax part

Criterion name	**Criteria**	**2D element**			**3D element**		
		No. of failed element	**[%]**	**Max/min value**	**No. of failed element**	**[%]**	**Max/min value**
Jacobian	< 0.7	771	1	0.34	21 919	27	0.20
Warpage	> 5°	16 151	24	108.72	46 242	57	108.72
Skew	> 60°	144	0	79.39	555	1	75.72
Aspect	> 5	729	1	18.77	1 680	2	13.65

Table 2. Numerical quality of personalized 5th model (622 case) – rib cage only

Criterion name	**Criteria**	**2D element**			**3D element**		
		No. of failed element	**[%]**	**Max/min value**	**No. of failed element**	**[%]**	**Max/min value**
Jacobian	< 0.7	824	1	0.34	22 101	27	0.15
Warpage	> 5°	17 721	26	106.60	50 551	62	110.49
Skew	> 60°	211	0	78.46	997	1	76.52
Aspect	> 5	1 110	2	26.14	2 047	3	17.55

Tables indicate that applied personalization method did not significantly changed the quality of the reference mesh even for 'making' the model and therefore all mesh elements smaller – like for 5th personalized cases.

Further application/utilization of developed personalized models allowed among others for:

1) Analyses of/comparison between completely different personalized geometries of chosen PMHS, taking into account individual characteristics of the occupant, regarding both the global and local geometry. It is illustrated in Figure 10 presenting comparison between 612 and 622 PMHS.

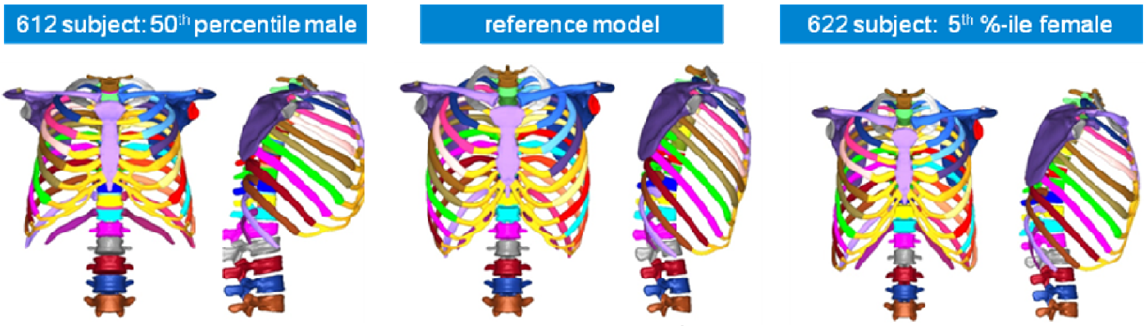

Figure 10: Two different target geometries comparison. 612 50th percentile male (left) and 622 subject – corresponding to 5th percentile female subject (right).

2) Analyses of/comparison between two models of the same subject – one generated with local personalization method and the second one by using a simpler, faster and without much specific in-depth data global approach. In the second method the internal segments (bones, organs etc.) are modified proportionally to the deformation of the external contour. Changes in rib's angle, thickness etc. are possible only in personalization method. (Figure 11)

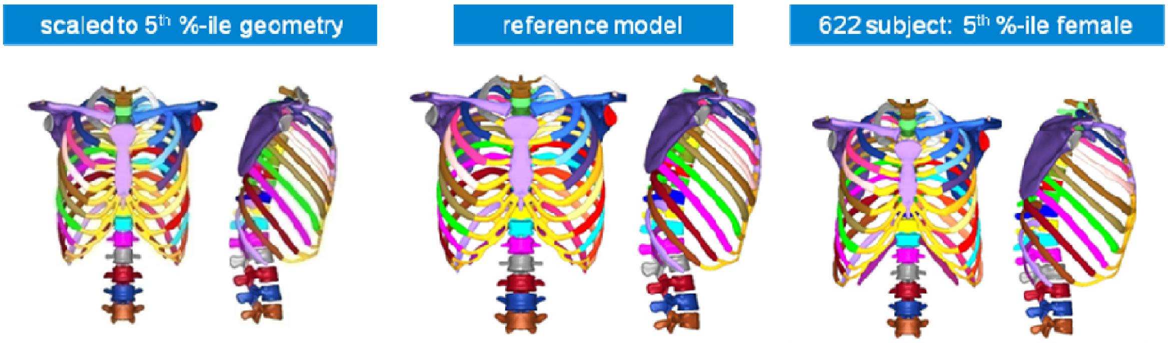

Figure 11: Globally (left) and locally (right) personalized target geometries comparison.

3) Mechanical response analyses – with direct comparison between cadaver and corresponding personalized model – gives unique opportunity to validate the model not only with respect to biofidelic corridors for chosen type of test and subject but also precisely compare model output signal with experimental one for corresponding subject. Figure 12 illustrates an example of compared signals. It indicates that in presented case, even having correct geometrical and mass representation, our model responded far from experimental data.

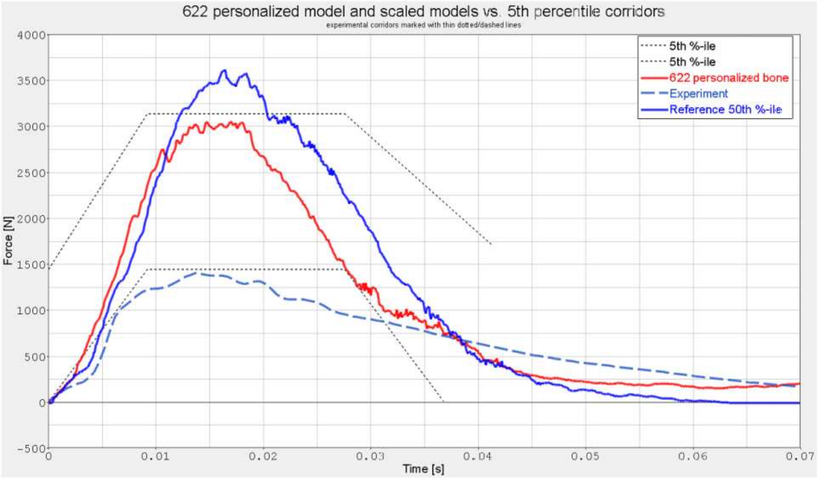

Figure 12: Exemplary impact force time history response in lateral test.

FUTURE WORK

Further improvement of the local personalization methodology is planned. It covers removing entirely or limiting the mesh tuning step, improving mesh quality close to control points locations, and addressing individual material properties of selected body parts, like for example rib cortical bone thickness distribution.

In terms of further work with THOMO model – it requires refinement mainly regarding soft tissue properties to have it well validated.

CONCLUSIONS

The THOMO model, at the current stage of development, allows for a wide range of parametric studies to mimic the variety of the vehicle users' population. Like most of the other available numerical human body models it requires further refinement/validation. The proposed personalization methods can be used for the further development of the human body model. Personalized model are valuable for the accident reconstruction and other biomechanical applications.

ACKNOWLEDGEMENTS

This study is a part of the THOMO project co-funded by the European Community FP7th. The authors would like to gratefully thank the European Community and the different partners involved in this project (http://www.thomo.eu/).

REFERENCES

HUANG Y., KING A., CAVANAUGH J. (1994). Finite Element Modeling of Gross Motion of Human Cadavers in Side Impact. Proceedings of the 38th Stapp Car Crash Conference, SAE Paper 942207.

LIZEE E., ROBIN S., SONG E., BERTHOLON N. et al. (1998). Development of a 3D Finite Element Model of the Human Body. SAE Paper 983152.

KIMPARA et al (2005). Development of a Three-Dimensional Finite Element Chest Model for the 5th Percentile Female. SAE Paper 2005-22-0012.

KROELL et al (1971). Impact Tolerance and Response of the Human Thorax. Proceedings of the 15th Stapp Car Crash Conference. SAE Paper 710851.

KROELL et al (1974). Impact Tolerance and Response of the Human Thorax II. Proceedings of the 18th Stapp Car Crash Conference. SAE Paper 741187.

MATHERTON G. (1973). The intrinsic random functions and their applications. Advances in Applied Probability, 5, pp. 439-468

PEDZISZ M., DZIEWONSKI T. (2012). Development of 5th and 95th scaled occupant thorax model. Influence of reference anthropometry data and kriging parameters on rib-cage shape and FE model dynamic response. Proceedings of the International Crashworthiness Conference. Milano. Italy. 2012-045

RUAN et al (2003). Prediction and analysis of human thoracic impact responses and injuries in cadaver impacts using a full human body finite element model. Stapp Car Crash J., 47, 299-321.

RUAN et al (2005). Biomechanical Analysis of Human Abdominal Impact Responses and Injuries through Finite Element Simulations of a Full Human Body Model. SAE paper 2005-22-0016.

TROCHU F. (1993). A contouring program based on dual kriging interpolation. Engineering with Computers, 9, 3, pp. 160-177.

VEZIN P., BERTHET F. (2009). Structural characterization of the human rib cage behavior under dynamic loading. Stapp Car Crash Journal, 53, November 2009.