HUMOS : HUMAN MODEL FOR SAFETY – A JOINT EFFORT TOWARDS THE DEVELOPMENT OF REFINED HUMAN-LIKE CAR OCCUPANT MODELS

Stéphane Robin
LAB PSA Peugeot-Citroën RENAULT, France
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ABSTRACT :

Car occupant safety is an increasing concern among car manufacturers, their suppliers, user organisations and legislative authorities. As for structural analysis, computer methods are more and more widely used to optimise the effectiveness of safety devices. However, no biofidelic numerical tools are currently available. Furthermore, there is a need for a future harmonisation of the methods and tools used. The HUMOS programme is a first step toward the development of commonly accepted models and computer methods. Fourteen partners were involved in this research programme, including car manufacturers, suppliers, software developers, universities and public research organisations. It was launched in December 1997 and is planned to be almost finished in March 2001.

The HUMOS programme though was conceived as a three-fold project:

- Synthesis and completion the current knowledge of the human body in terms of geometry, kinematics behaviour, injury threshold and risk.
- Implementation of this knowledge in new human body models.
- Development of the utilities for the design office use, and delivering of the models available for their integration in the car design process.

A wide bibliographical review supported those major goals. Afterwards, the geometry acquisition of a mid-sized male in a car driver seated position was achieved. The main human body structures were then reconstructed using a CAD method and delivered to the so-called 'modelling partners'. The meshing of the different structures was achieved based on the CAD definition and led to models accounting for skin, bones, muscles as well as the main organs (lungs, heart, liver, kidneys, intestine etc.). The validation process was undertaken on a segment basis, each main part of the human body being confronted to the available literature results. The assembly of the whole model will be the conclusive part of this programme.

INTRODUCTION:

During the last three decades, car manufacturers, their suppliers, user organisations and legislative authorities have manifested an increasing concern about car occupant safety. Nowadays, passive safety requirements are determining factors in the car designing process. More and more sophisticated tools are needed though, among whose computer tools are becoming more and more popular. The development of simulation tools is one of the most promising future field of investigation, but a lot of knowledge still needs to be generated in order to improve the ability of those tools to predict the occupant behaviour in car crash conditions.

The currently used anthropomorphic crash test dummies are limited in their biofidelity and in their application type (frontal, lateral…). They however were modelled using computer techniques in order to improve the optimisation process of safety devices. But these models inherited the shortcomings of their physical counterparts. Dummies and dummy models however enabled car manufacturers, in the past years, to significantly increase the passive safety performances of their vehicles. Most of the current safety devices indeed were developed with the well-known Hybrid III frontal dummy or EuroSID 1 side impact dummy.

Now, the high level of passive safety reached by most of the current vehicle leads to a new challenge for carmakers and suppliers, which is the optimisation of the safety devices for a more humanlike substitute. If the physical dummies still enable to assess the passive safety level of a car, further enhancements should be achieved using more biofidelic tools, and probably more refined and sophisticated computer models.

The basic assumption of the HUMOS programme is thus that a biofidelic model shall be structurally very close to the real human body. This assumption means that a correct representation of the main human structures is needed, most of the bony parts of course, but also the main organs and muscles. Afterward, a basic knowledge is also needed in order to provide the model with a satisfactory mechanical behaviour in a car crash situation.

The first problem that had to be solved was the acquisition of the inner and outer geometry of a human being in a car occupant posture (the driver posture was chosen), and there is at the moment no systematic method, which enable this acquisition. Some research work was carried out in the past, and the publication made by Robbins [1] served as a basis for many developments of human substitutes. This work mainly qualified the position of external anatomical landmarks on many different car occupants. But there were some limitations in this work, particularly concerning the relative position of the different bony structures and of the different organs.

Within the HUMOS project, an investigation work was carried out to define a first reference geometry of a car occupant, including bones, organs and muscles.

The second problem was the generation of a enhanced knowledge about the mechanical behaviour of a car occupant. Within the HUMOS programme, different studies were undertaken. A literature review enabled to build a first validation database. This database was enhanced by some experimental investigations, both for some material laws and behaviour and for the human global behaviour.

The work achieved in the course of the HUMOS project led to a first human model, partially shared by three different dynamic simulation software. This model is probably the most refined finite element human body model ever built, and will constitute in the future a reference model for further developments. It is already validated, as far as the different segments are concerned. The global validation in different car crash situations still needs to be achieved. At the end of the validation process, this unique model will possess multi-directional capabilities and will lead to more refined pieces of information in complex situations, like oblique or rollover crashes. This model was designed as a reference for future developments (pedestrian modelling for example). It was organised in a way that renders it possible some further refinements, or even partial refinements if needed. It will finally be possible to use this model outer the automobile field, in other transportation fields.

This model finally has some limitations. The primary limitation is its geometry, which is frozen, not far from the 50^{th} centile adult male driver. More studies are needed in order to be able to define different occupant geometry. The second limitation is its mechanical definition. Lots of data is still needed for a correct definition of the behaviour of some organs, and of the muscles. Finally, very few relationships are currently existing between the model behaviour and the correlated injury risk. Those different points were partially addressed by the HUMOS programme, but as preliminary investigations. The model however should be a very efficient tool for a further investigation of these different issues.

MAIN OBJECTIVES:

The main initial objective of this work was to build a refined human body model that could be widely accepted by the crashworthiness community. As a first step, it was decided to define a so-called kinematics model, but with some extension capabilities. It was indeed assumed that the three years time frame originally planned was too short for the building of an injury predictive finite element model, the main reason being that a lot of knowledge still needs to be generated as far as the different injury mechanisms are concerned. As a first step though, it was decided to gather the most advanced current knowledge of the human body behaviour in car crash conditions into a unique computer tool. Generating new knowledge about injury mechanisms was considered beyond the scope of the programme. It was foreseen however that a good anatomical description was a prerequisite for further enhancements of the prediction capabilities of the model. Thus, for example, the surfaces of the most important joints of the human body were accurately defined. The modelling of the mechanical properties of these joints was carried out using 3D generalised springs, which is satisfactory when kinematics parameters are observed, but not when injury mechanisms are sought. It is possible however to further refine the definition of those joints.

It shall be emphasised that injury prediction will be possible to a certain extend thanks to the currently used injury threshold as far as the concerned criteria are derived from kinematics values. For example, the validation of the thoracic behaviour is largely based on the sternum deflexion. This example is relevant for explaining what is the difference between a kinematics criterion and a criterion related to an injury mechanism. In most of the currently available data dealing with thoracic deflexion, rib fractures were observed. The sternum displacement in this case cannot be considered as reversible. A model accounting for an injury mechanism shall be capable of representing rib fractures, and thus the non-reversibility of the thoracic deflexion. A purely kinematics model will only account for the relationship between the model deflexion and the risk of rib fractures. It was decided that only this second validation level would be considered for the HUMOS model. It is the reason why this model is called a “kinematics” model.

The second main objective of the project was to build a first reference mesh suitable for further developments. It was indeed identified at the beginning of the programme that some limitations in the modelling of a human being were associated with some lack of information concerning the inner geometry of the human body. In particular, the relative position of the different organs one with regard to the other was partially unknown for an occupant in a seating position and very few techniques were available for achieving this description. The best solution would have been to describe the complete geometry of a wide range of population and to define accordingly the 50° percentile. It appeared to be unrealistic. The choice made for the HUMOS project is to accurately define the complete geometry of a subject as close as possible to the 50° European adult male driver. It is expected that in the future, some scaling techniques would enable to modify this reference mesh in order to derive different models (5°, 50° and 95° percentile occupants for example). A first attempt was made during this programme to define the main parameters describing these different occupants, but some further research is still needed in this field.

METHODS:

The multidisciplinary HUMOS project was organised around different tasks.

As far as the building of the finite element model is concerned, the first task to achieve was the geometry acquisition, both inner and outer the human body. For this task, anatomists and computer people worked together in order to provide CAD-like description files to the modelling people. The method used was previously experimented by a medicine university and refined in order to provide the HUMOS programme with up-to-date geometrical data. The resulting files were used to build the mesh of the final model. The geometrical description of the human body included the bony structure, the main muscles and ligaments, the most relevant organs, and the skin contours. The finite element model was built segment by segment, by different partners of the project, and assembled together at the end of the process. A special attention was paid to the liability and the robustness of the different models. Furthermore, the final assembly was carried out keeping it possible to replace some parts of the model with coarser or more refined segment models.

In parallel, some investigation work was carried out on material behaviour. New experimental data was generated also dealing with the whole human body in a car crash situation. A wide validation database was built gathering the result of the literature review together with the new knowledge generated within the programme.

GEOMETRY ACQUISITION:

Geometry acquisition:

The geometry acquisition of a seated human being was a core activity within the HUMOS programme. It aimed at the definition of the position and the volume of the different anatomical structures of a 50th percentile adult male driver. A medicine university was able to carry out this work. A previously developed protocol was further enhanced and used in order to provide the HUMOS project with a refine anatomical description of the human body in a car seated position. The main challenge for this activity was dictated by the available human geometrical database. The main external dimensions of the human being indeed are available in commercially available database. But some information is missing concerning the geometry of the different organs and the positions of the different structures, one with regard to the other, in a seated position. Furthermore, very few acquisition techniques are available nowadays that enable to simultaneously acquire the inner and outer geometry of a seated car occupant. The best solution would have been to systematically acquire the geometry of a great number of very different people, and then to carry out a statistical analysis of these acquisitions. But x-ray CT-scan techniques nor MRI techniques enable to achieve the complete acquisition of a seated man. I had been envisaged to try to carry out the acquisition of lying subjects, and afterwards to try to correlate the results in a lying position with some coarser results obtained in a seating position. It was however judged beyond the possibilities of the HUMOS project.

The method chosen was thus very manual. It is the physical slicing of a frozen cadaver, which was carried out. It was known from the beginning that the choice of the subject would be one of the most determining factor of the quality and representativeness of the result. A particular attention was paid to the choice of the subject. The sitting height was considered as one of the most important factor for securing the choice of the subject. The following table summarises the main characteristics of the HUMOS subject and those of the 50° percentile European male.

Table 1: main characteristics of the HUMOS subject compared with the 50° percentile adult male.

	Sitting Height (mm)	Standing Height (mm)	Weight (kg)
HUMOS subject	920	1730	80
50° centile European Male	915	1750	75.5

The subject was thus not far from the 50° centile European male. The x-ray examination only revealed a slight pulmonary asymmetry. Furthermore, the subject has some of the characteristics of elderly people, that is to say thin upper and lower limbs and some fat tissues around the abdomen and the thorax.

It was thus a particular anthropometry that was digitalise and accounted for by the model.
The method consisted of first securing a cadaver in a driving position (see figure 1).

Figure 1: HUMOS subject in its initial driving position.

A standard full-size car cockpit was used to this end. The subject was installed in a driving position, hands secured on the steering wheel, and then frozen in this position. A reference frame related to the cockpit was defined and the subject was embedded in a polymer block. The slicing process was then carried out.
Each slice was 5mm thick, and the saw was 2.5mm thick (268 slices were realised). The different slices were photographed on each side (491 images) and then each image was contoured, organ by organ, by skilled anatomists. This acquisition phase generated a set of about 13.000 files representing 300 different organs. Each file was composed of a set of points characterised by their 2D coordinates related to the slice. Each slice's position with regard to the reference frame was also available in the different files. A 3D visualisation based on the nodes was carried out in order to validate the acquisition process and, if need be, to modify some of the points describing the organs. The three-dimensional reconstruction of the acquisition is reproduced on the following figures (2, 3 and 4).

3D geometrical reconstruction:

The following step in the geometrical definition of the human being in a seated position was the three-dimensional reconstruction of the anatomical data previously generated. Roughly speaking, this task consisted in the transformation of the point-by-point description files into CAD geometrical files. Standard commercially available CAD software was used to this end. The main organs were reconstructed using available mathematical surface definitions. A back and forth process was set up between anatomists and CAD engineers in order to double-check at each step the shape of the reconstructed surfaces. The CAD reconstruction being one of the main parts of the reconstruction process, some assumption were needed during this phase. They were thoroughly discussed with anatomists.

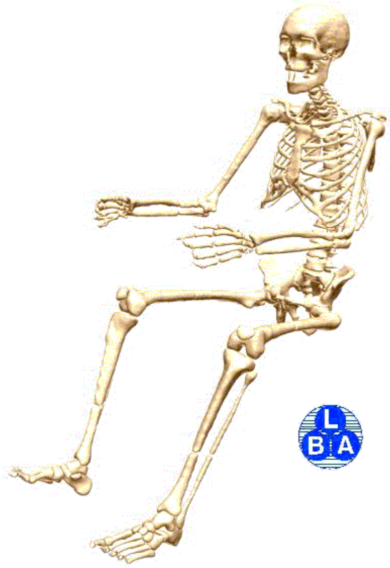

Figure 2: 3D visualisation of the bony parts acquisition result.

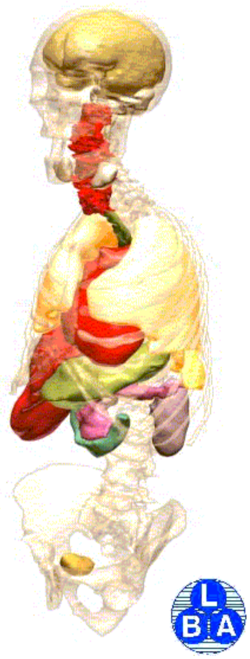

Figure 3: 3D visualisation of the main organs acquisition result.

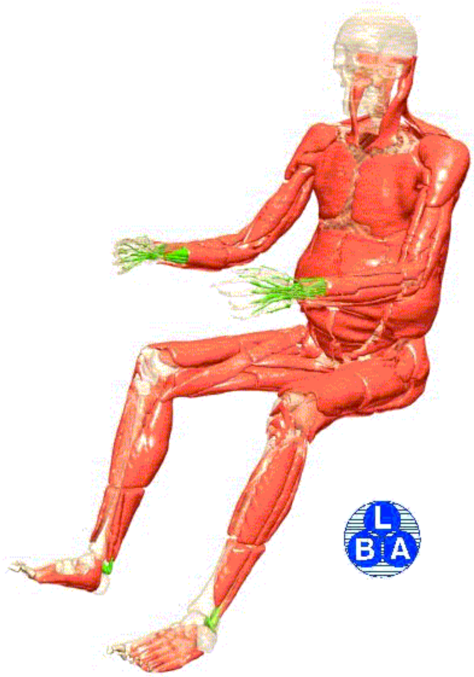

Figure 4: 3D visualisation of the whole acquisition results (without the skin).

Meshing process:

The meshing process was a joint effort carried out by different partners of the programme, depending upon their experience on the concerned segments. The homogeneity of the meshes was checked step by step in order to insure the feasibility of the final assembly of the model. During this process again, a close collaboration was maintained with the anatomists in order to double-check the shape of the reconstructed organs as well as the validity of the assumptions made. It is for example to be noticed that only half of the skeleton was meshed. A sagittal symmetry was assumed for the second part of the skeleton. This first assumption had some influences on the rest of the meshing process. The lungs are not symmetrical indeed, and some slight geometrical modifications were made in order to adapt the lung external surface to the chest internal shape. Further assumptions were made for some parts of the human body, which were not described accurately enough. For example, the posterior archs of the different vertebrae were not always visible. In the same manner, all the ligaments and muscles were not digitised during the acquisition process. Thus, some assumptions based on anatomical descriptions were made in order to add some muscle parts and some ligaments.

The new constraints discovered during the meshing process were the result of the requirements commonly agreed at the beginning of the programme. Indeed, it was decided to try to keep the number of deformable elements lower than 50.000. Some requirements were described also on the final time step of the complete model and had some consequences on the minimum size of the elements.

The following figures illustrate the different segment meshes developped during this process.

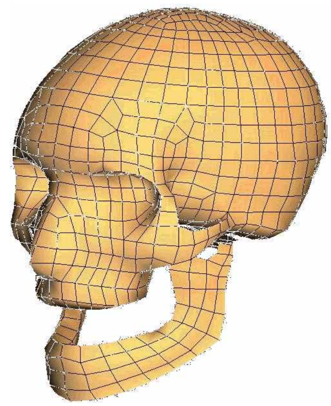

Figure 5: mesh of the bony part of the skull.

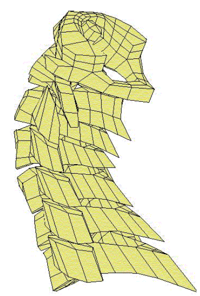

Figure 6: mesh of the cervical vertebrae

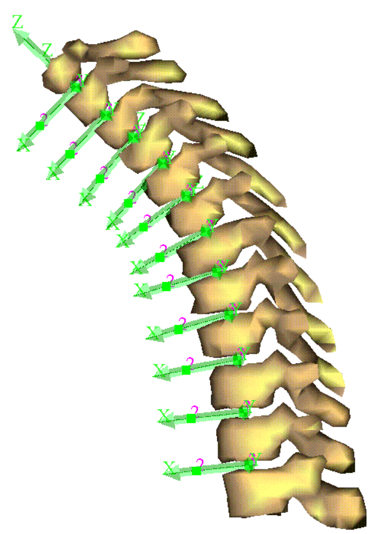

Figure 7: model of the vertebral column. The intervertebral discs are modelled as 3D spring elements.

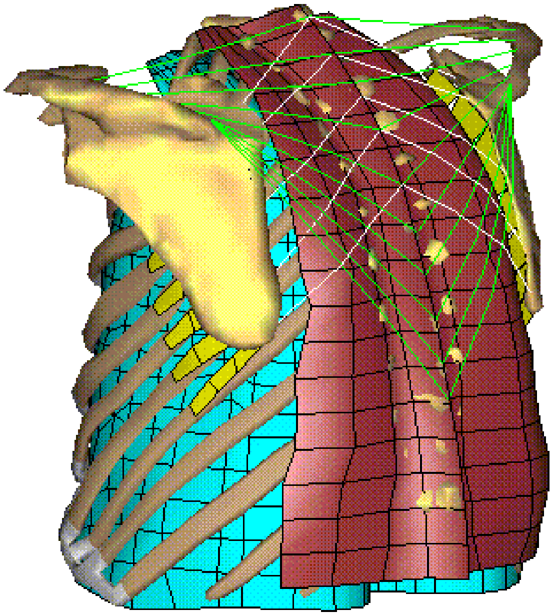

Figure 8: mesh of the chest segment

The final mesh of the whole thorax is a good example of the work carried out during this phase of the programme. The clavicle, sternum, ribs and connective cartilaginous structures were modelled using shell and solid elements. The scapula and the different vertebrae were modelled using shell elements for the definition of the shape of those structures. In the mechanical model, these bony parts are described as rigid elements. The muscular structures were meshed using both truss and solid elements. The flesh and connective tissues were modelled using brick elements.

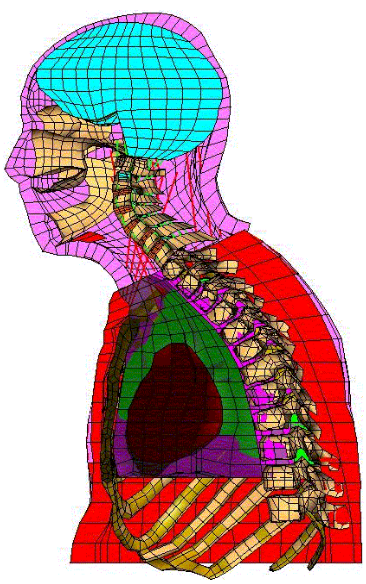

Figure 9: sagittal section of the mesh of the upper body.

Segment validation process:
The following activity of this programme consisted of providing mechanical properties to the different constitutive elements of the model. The validation process was carried out on a segmental basis.

As far as the material properties are concerned, they were mainly derived from the literature review carried out within the programme. The validation corridors published by Lizée et al. [2,3] were used to this end. Some further improvements were made based on the experimental work carried out during the programme. As an example, the rib models behaviour were first checked against static and dynamic tests carried out on isolated human ribs. The ribs were modelled using shell elements for the cortical bone and solid elements for the trabecular bone. Node sharing was assumed for the description of the connection between both tissues. The thickness of the cortical bone was modelled using different shell thickness depending upon the location. In order to increase the time step, some assumptions were made concerning the density of the different parts of the rib. The cortical bone density of the models was increased while the trabecular bone density was decreased. Among the experimental results available in the literature, the different authors reported a lot of rib fractures. In order to account for this phenomenon, a failure plastic strain was introduced in the rib material law. The different values used for the material behaviour definition of the ribs are reported in the following table.

These values were used for both the static and dynamic validation of the ribs behaviour. The following figure illustrate the static behaviour of the so-called “HUMOS rib” compared with the results obtained on a isolated human rib by Heidelberg University.

Rib cortical bone material model: elasto-plastic behaviour with failure.	
Elasticity modulus	14 GPa
Yield Stress	70 Mpa
Ultimate stress	70 Mpa
Maximum deformation	4%
Poisson’s ratio	0.3
Density	6000 kg/m^3

Table 2: material properties of the ribs cortical bones.

This first definition of the rib model was double-checked against the whole thorax behaviour. It was observed that the isolated model was a bit too soft as far as its dynamic behaviour was concerned. Raising the static yield stress of the cortical bone could have solved this problem. However, in this case, the whole thoracic cage would have exhibited a too stiff behaviour with regard to the available experimental results. The validation level however was judged satisfactory. It is to be mentioned that the location-dependent stiffness of the rib was not homogeneously distributed, but that only four different thickness were used. It partly explains the discrepancies observed between experimental and computer results. This simplification is needed however to keep the model usable.

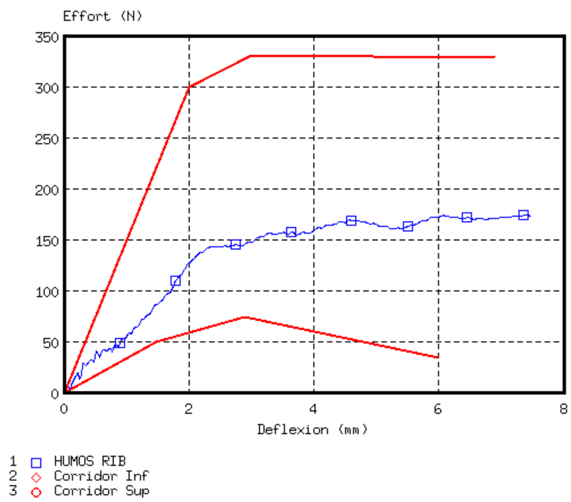

Figure 9: computer result compared with experimental corridor of an isolated rib subjected to a quasi-static loading.

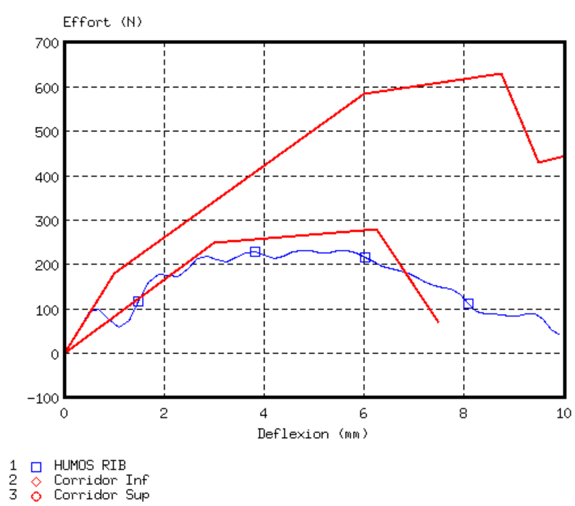

Figure 10: computer result compared with experimental corridor of an isolated rib subjected to a dynamic loading.

For the bones and cartilaginous parts of the thorax for which some experimental data were available, the same process was used for the first description of the model. Afterwards, the assembled segment models were validated against the published experimental results. As an example, the following figures represents the results obtained for the thorax as compared to the experimental results published by Kroell et Al. [4,5]. In these experiments, the thorax was hit by a 23.4 kg cylindrical impactor at 9.9 m/s.

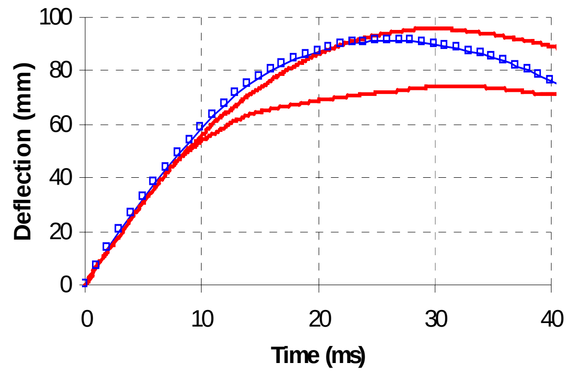

Figure 11: deflection versus time.

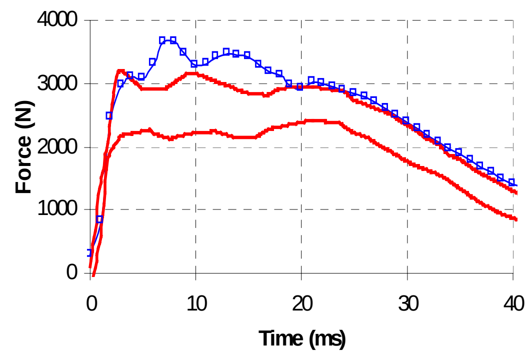

Figure 12: impactor force versus time.

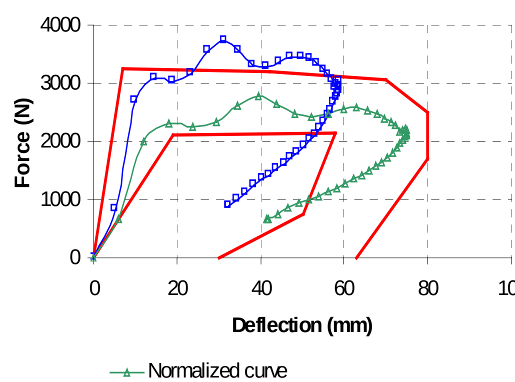

Figure 13: force-deflection curve.

In the force deflection figure (figure 13), a normalised curve was also added. The method proposed by Mertz [6] was used and adapted to account for the variation that could be expected from the HUMOS subject with regard to a 50^{th} percentile subject. This curve exhibits the thoracic weight difference of the HUMOS subject, and its influence as far as the global behaviour is concerned.

MATERIAL LAWS:

In order to provide the model with up-to-date material properties, some investigations were carried out within the course of the project. First of all, a wide literature review enabled to gather the available knowledge and to identify some lack of information. For hard tissues, ribs, clavicles, sternum and pelvis bone material properties were identified as poorly described in the literature, especially concerning the dynamic behaviour of those structures. Soft tissues, in particular muscles material properties are also poorly described in the literature. Consequently, some experimental static and dynamic tests were achieved within the programme.

Ribs, clavicles, sternum and pelvic bone were tested extensively in order to gain some knowledge about their mechanical properties. A wide set of experiments was carried out. Those results were associated with the definition of a parameterised material law (a power law was used). Different parameters were specified for the different human bones.

Furthermore, some static and dynamic muscle tension-compression experiments were carried out. The strain-rate sensitivity was quantified for those soft tissues. The idea was for soft tissues the same as for hard tissues, i.e. to built a physical parametric material law which could have been used for different biological soft tissues. Some existing laws were adapted instead and implemented in the different available software.

For the different organs, very few experimental results are available and there is an obvious lack of knowledge in this field. Linear visco-elastic laws were chosen, according to other modelling publications. Soft tissue characterisation is still regarded as a largely uncovered area.

DISCUSSION AND CONCLUSIONS:

In the view of designing a widely accepted human body model, a joint effort between some car manufacturers, suppliers, software developers, public research institute and universities was undertaken.

This programme led to a first definition of a refined finite element model of the human body in a driving seating posture. This model was implemented with three main dynamic computer codes: MADYMO, RADIOSS and PAM-CRASH. This point is of importance, one of the objectives of the programme being to design a widely accepted model. The mesh of the model is shared by the different software packages. The validation of the different models was carried out separately for the different codes.

A large validation database was build and used in order to validate the different segments of the model. The global validation of the whole model still remains to be done. Unfortunately, it is currently still difficult to account for the proprieties of living subjects, and as far as the mechanical behaviour in car crash conditions is concerned, mainly cadaver results are available in the literature. Some investigations still need to be carried out on the muscle tone contribution, especially for the low speed impact conditions that can be encountered in real field accident analysis. Furthermore, some limitations are due to the lack of knowledge of the injury mechanisms. The main currently used criteria were implemented in the model, but its injury prediction capabilities are limited with regard to its complexity.

From the beginning of this research work, it was foreseen that some major limitations would be met. First of all, the geometrical definition of the model which is refined, but which comes from a unique specimen, with some particularities. It is expected in a follow-up programme to be able to describe scaling techniques which would enable to first define a 50° centile model from the current reference mesh, and second 5° and 95° percentile occupant models. It is also expected to be able to derive from this first model some pedestrian models.

It was also identified during this work that some knowledge is missing as far as the soft tissues behaviour is concerned, and also the muscle tone contribution in some crash conditions. It is expected that the model itself, which is accounting for the main muscular structures and the main soft tissues will enable to carry out parametric studies aiming at evaluating the muscle contribution and also at the assessment of some suspected injury mechanisms.

CONTRIBUTING PARTNERS:

As emphasised in the title of this paper, and throughout it, the development of the HUMOS model is a joint effort between many partners. The LAB (Laboratory of Accidentology and Biomechanics PSA Peugeot Citroën Renault) insured the co-ordination of the work and was involved in many parts of it, mainly the meshing process of the thorax and the validation database. The other car manufacturers involved were Volvo (meshing of the neck), BMW (meshing of the upper limbs), and VW (literature review of the existing models). Software developers were strongly involved in this programme. ISAM/MECALOG (Radioss software) carried out the 3D CAD reconstruction of the model, the head mesh description, and insured the assembly of the final model with Radioss. ESI (Pam-Crash software) modelled the lower limbs and was in charge of the homogeneity of the different segment models. ESI also insured the assembly of the final model with Pam-Crash. TNO carried out the modelling work under the Madymo software, and co-ordinated the soft tissue behaviour activities. The supplier FAURECIA carried out the pelvis and abdomen modelling and co-ordinated the geometry acquisition process. INRETS carried out full-scale sled tests with human substitutes and contributed to the extension of the validation database. Athens University carried out a tentative research work aiming at the definition of physical material laws for the different human soft tissues. Athens University also carried out an experimental work on some muscle properties. Heidelberg University was in charge of experimental investigations on different human tissues (bones and some cartilaginous structures). It delivered a wide set of new experiments to the HUMOS consortium and contributed to the extension of the validation database. Chalmers University achieved a wide bibliographical study on the current knowledge about human tissue behaviour and identified the fields of missing knowledge. Chalmers University contributed in the validation of the neck model. Marseille University was in charge of the geometrical acquisition of the seated human body. This work was carried out by the Laboratory of Applied Biomechanics.

ACKNOWLEDGEMENT:

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