FE Human Modelling in Crash – Aspects of the numerical Modelling and current Applications in the Automotive Industry

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Abstract:

Human modelling is a rather new development in occupant and pedestrian safety simulations in the automotive industry and gained much importance and interest in recent years. However it is still in a very early development phase and the model development and validation is still under heavy development. The general intention of these models is to incorporate the biomechanical aspect into pedestrian and occupant safety simulations and to enhance the significance of conventional dummy models. Especially the prediction of injuries in a crash situation is a very important task.
This contribution will introduce the particular human model THUMS (Total HUman Model for Safety) and focus on some numerical and algorithmical aspects, important for a successful use of the model in automotive crash simulations. Finally, some examples using the occupant and pedestrian version of the THUMS model will be presented and discussed.

Keywords:

THUMS, Human Modelling, dummy models, pedestrian and occupant safety simulations, crash tests

1 Introduction: From Dummy Modelling to Human Modelling

Software dummy models are nowadays the standard tool to represent the human body in pedestrian and occupant safety simulations. These conventional dummy models are generally designed as numerical models of their respective hardware counterparts and usually represent a standardised, average stature of the human body. Here, the average 50% American male (AM50) or the 5% American female (AF05), a rather small female model (statistically, only 5% of the American females are smaller) are for instance considered. Due to cost reasons and reasons of sustainability, the hardware models are firstly required to endure multiple crash tests and crash situations and secondly have to ensure the repeatability of the results.

As a consequence, these models consist of a very robust structure, incorporating a considerably simplified geometry and simple materials, like steel and foam or rubber materials. Additionally, the joints are approximated as rigid-body joints, using a fixed centre of rotation or rotation axis and internal organs are generally only allusively included. Fig. 1 shows some details of the numerical Hybrid *III* front crash and the numerical *EuroSID II* side impact dummy models.

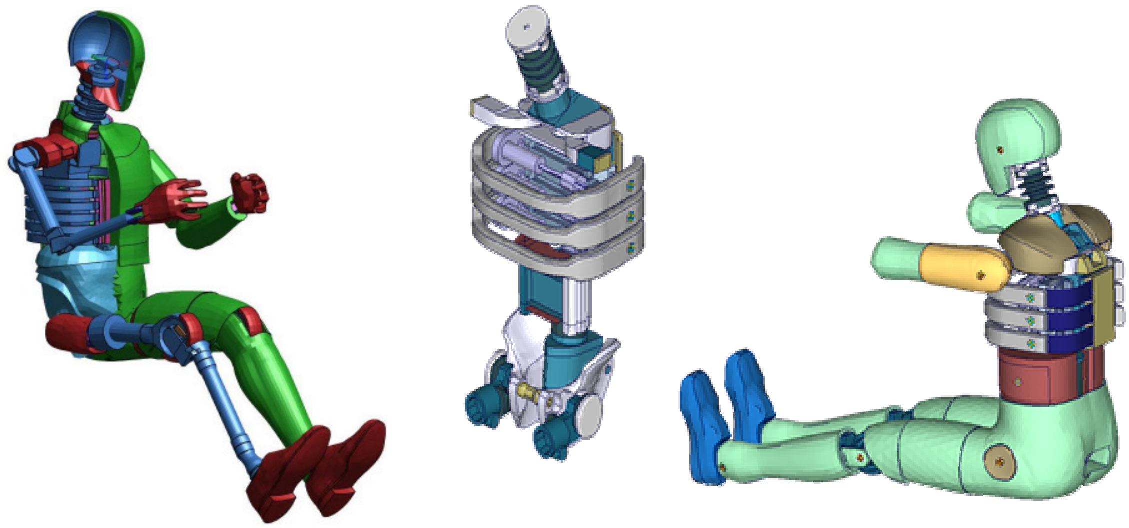

Figure 1: Hybrid III and EuroSID II dummy model details

The main reasons for the development of these dummy models (real-world and numerical models) was the inclusion of the human aspect into automotive crash situations, where for instance passive safety systems, like airbags, seatbelts or other protective paddings have to be developed and properly dimensioned to satisfy increased safety requirements and to decrease the injury risk in real-life accident situations. This led to the development of multiple different models for front crash simulations (Hybrid III), side crash (WorldSID, EuroSID) or rear impact simulations (BioRID).

Another important aspect, especially of the numerical dummy models, is the assessment and prediction of these injury risks that might occur in an accident situation. The injuries in question may include neck injuries or whiplash in rear or side impact crash situations, bone fractures or injuries to the internal organs. Therefore, the accelerations, deflections and intrusions of certain body parts are measured during the simulation and correlated with human injuries via so-called *injury criteria*. These criteria are mostly statistical and are often based on evaluations and observations of real-life accidents or laboratory test results. However, because of the rough representation of the human anatomy, this approach allows only very limited possibilities for the assessment and prediction of injuries. Failure of bones or tissues, for instance, can generally not be modelled using this approach. Additionally, the quite large deformations of the internal organs in a crash situation are hardly represented at all. Consequently, the question might occur, whether the use of (numerical) dummy models is still representative and able to replace the human body in the vehicle design and optimisation process.

For these reasons, the development of numerical models of a realistic human body was initiated and enforced within the last decade and these models recently gained much importance and attention in the automotive industry. By modelling bones, soft tissues, flesh, fat and internal organs, these models are designed as a more realistic image of the real human body and they include improved capabilities to consider also biomechanical responses for improved injury predictions. In theory, it is even possible to distinguish between different kinds of injuries, for instance the instantaneous and irreversible mechanical damage of fractured bones or damaged tissues on the one hand and the reduction of physiological functions, like e.g. damage of internal organs or the brain on the other hand. In fact the first point is already implemented by using appropriate material and element failure formulations and criteria.

However, the present models are still in a very early development phase and only represent the first generation of productive human models. But they are already widely used and the first, successful and promising results were already obtained. However, the internal geometry, i.e. anatomy, of a real human body is extremely complex. Additionally, the available numerical algorithms are also limited in their efficiency and accuracy. In this sense, a trade-off has to be accepted between the computational efficiency, the robustness of execution and the accuracy. This means that for stability reasons, the detailing of the internal and external geometry of current models is partly still very rough and as the computation power increases and the underlying numerical algorithms are getting more stable, finer models are still being developed.

Currently, a number of human models is already in use by different automotive companies. For instance, the *H-Model* was developed by ESI [1] for the explicit finite element code *PamCrash* while the models *HUMOS-1* and *HUMOS-2* (*HUman MOdel for Safety*) were developed within the European project *APROSYS* (*Advanced PROtection SYStem*) [2], for the *RADIOSS* finite element software. This contribution will give a description of the particular human model *THUMS* (*Total HUman Model for Safety*) [3,4], which is available for *LS-DYNA* and will especially focus on various numerical aspects, arising from the detailing of the model. Sources of problems, as well as possible further improvements of the model and requirements to the numerical algorithms will be addressed and discussed. Finally, some applications from the area of pedestrian and occupant safety will be given.

2 Brief Description of the THUMS Model

The *THUMS* (*Total HUman Model for Safety*) is currently being developed by *Toyota Central R&D LABS* and the US-American *Wayne State University*. The first model was completed in 2000 and represents the 50% American male (AM50) [3], which represents an average American male with a body size of about *180cm* and a weight of *79kg*. In the meantime, it is available as an occupant and a pedestrian model (see Fig. 2). Although both models are very similar, there are slight differences in the structure, according to the respective demands and the corresponding crash situations.

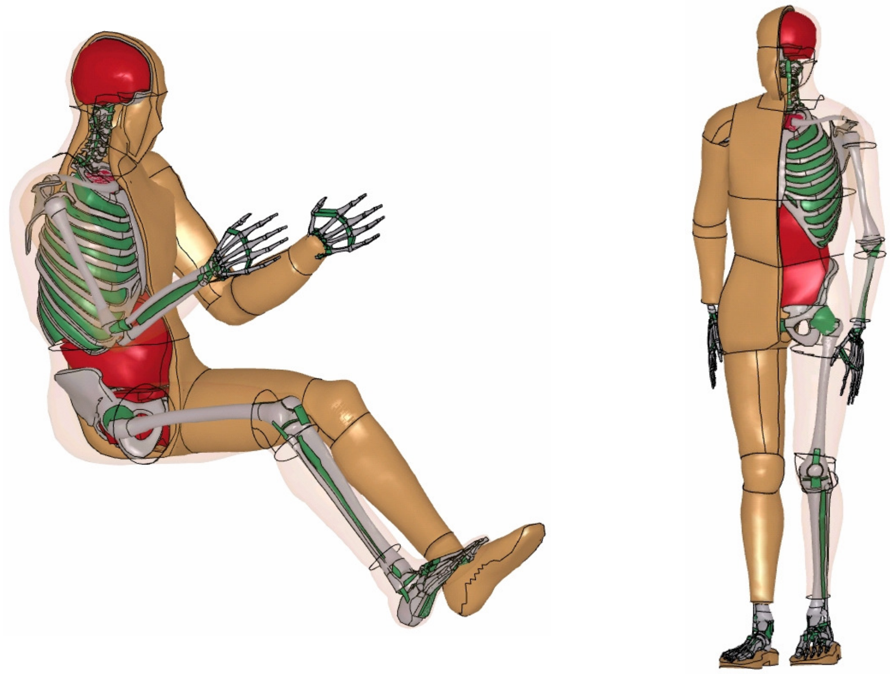

Figure 2: Occupant and pedestrian AM50-THUMS model

Generally, both models include a very detailed skeletal structure (Fig. 3) with a detailed representation of the cortical and the cancellous or spongy bones using shell and volume elements, respectively. The joints are modelled realistically using bone-to-bone contacts, as well as ligaments and tendons to enable a physically meaningful relative motion of the limbs. The spine is another very detailed part of the model, where the vertebrae, the intervertebral discs as well as reinforcing muscles are included using beam or discrete element formulations. However, no active muscles are considered within the current models yet. In fact, it is generally not clear, whether active muscles would have any influence on the overall motion of the model within a crash situation with an approximated duration of about *50-150ms*. The current models behave more like dead body models. However, this is currently under heavy development by different research institutes and companies and future models might therefore include active muscle systems.

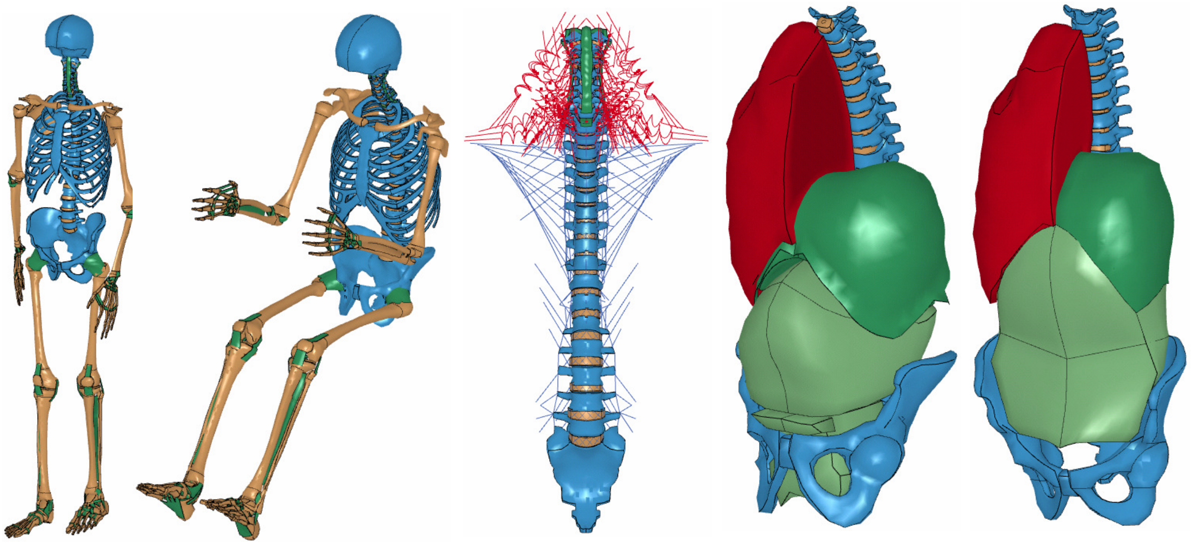

Figure 3: Details of the THUMS model; skeletal structure, spinal and muscular system and internal organs (pedestrian and occupant model)

The internal organs are represented in terms of the pulmonary area (lungs) and the abdominal area (stomach and digestive system), which are modelled using volume and shell elements for the respective cortical layers. For stability reasons, these two areas are modelled coherently and without a detailed representation of single organs (cf. Section 4).

In recent years, additional interest was developed in the *5% female* and *6 year-old child* model by different automotive companies. The 5% female represents a rather small female model, with a body size of about *160cm* and a weight of *49kg*, while the 6yo child model has a size of *120cm* and a weight of *20kg*. Because of the smaller model size, the motion sequences, for instance in a pedestrian accident simulation, is entirely different, compared to the AM50. Consequently, this leads to different impact areas on the vehicle and might also have to be considered in the optimisation and development process of the vehicle. Furthermore, different potential injuries might be experienced in a crash situation, since the area, where the vehicle impacts the pedestrian model differs considerably.

Unfortunately, these models are not yet available from Toyota and the models shown in Fig. 4 have been derived from the AM50 model using appropriate scaling, morphing and remodelling techniques to adapt to the different body statures and weight distributions.

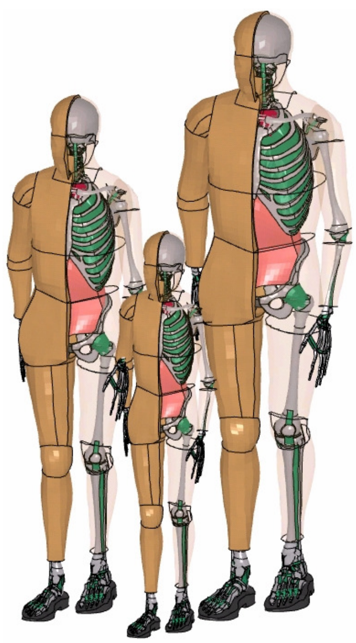

Figure 4: THUMS family: AF05, 6YO, AM50

3 Model Validation

The model validation is a very important aspect to ensure and revise the ability of the model to reproduce the physical behaviour of the real human body for the respective crash situations satisfactorily. The validation is mainly performed using pendulum tests against certain model parts, where impact forces and the corresponding intrusions are evaluated and compared to experiments, either cadaver tests or voluntary tests. These pendulum tests can for instance include the chest (lateral and frontal), pelvis (lateral) or the head (lateral and frontal). The validation is an entirely different chapter and should not be addressed here in more detail. Further information can for instance be found in [5] or [7], where examples and results are given. A more general overview can be found in [8].

4 Some Aspects of the Numerical Modelling

Apart from dealing with a more realistic model of the human body, the main reasons for the application of the THUMS model are probably the considerably enhanced capabilities to predict injury risks for various crash situations. These injuries can be physically modelled and do not have to be derived from measurements and statistical injury criteria. However, this certainly requires a rather high degree of model complexity and areas, where injuries are usually expected, have to be modelled with a high attention to the detail.

These areas may include for instance the lower extremities, like knees, feet and the hip, the spine, the thorax and the neck, resp. the head, as well as the internal organs, in terms of the abdominal (stomach) and pulmonary (lung) areas. Fig. 3 shows details of the skeletal system and the internal organs for the pedestrian and the occupant models. Note that the modelling of the internal organs is still very rough and no single organs, like for instance the liver, kidneys or the spleen are available. However, the inclusion of more detailed internal organs is currently under heavy development, but due to fairly large deformations of the relatively soft internal organs, it is very hard to ensure numerical stability of the model throughout the crash simulation. Therefore, as a first step, the geometry is chosen to be as simple as possible, since a further subdivision into single organs, including a far more complex geometry and additional contact conditions between the organs, would lead to a considerable decrease of the numerical stability. Further examples and comments concerning this problem will be given in the example section.

Another important point is that in conventional dummy models the joints between different model parts are usually connected using rigid body joints. Despite of being numerically very stable, they introduce a considerable limitation for the body movements and are thus not able to reproduce the physical motion of the body in a crash situation. In fact, their behaviour can be too stiff in some situations. The human models on the other side, consider realistic joints without a fixed axis or centre of rotation. The degrees of freedom of the joints are rather defined by contact conditions and interactions with tendons and ligaments within the joints. Fig. 5 shows some details of the elbow, knee and foot joints.

Finally we also want to focus on „good FE modelling“, where predominantly „well-shaped“ hexahedral and quadrilateral elements for accuracy reasons should be used. Because of the very complex geometry, this is of course very difficult to achieve for the whole model and therefore, the THUMS model is subdivided into smaller parts, which are meshed solitary. These parts are then reconnected using penalty- or constrained-based tie contact conditions (cf. e.g. the connection between the pulmonary and the abdominal area of the internal organs in Fig. 3).

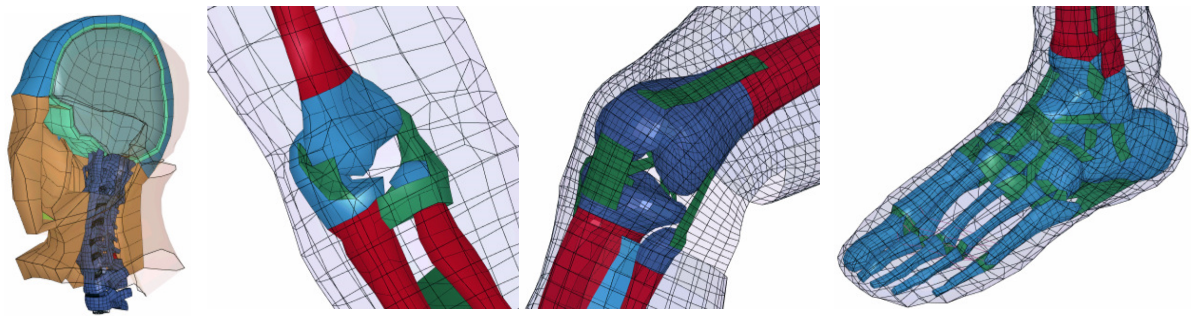

Figure 5: Details of the THUMS model; head/spine connection, elbow, knee and foot joints

5 Difficulties in Modelling and Algorithms

Unfortunately, the detailing of the model might lead to some difficulties from the numerical and algorithmic point of view. Because of the complex geometry, these difficulties are somehow special for the human model and may often lead to an early breakdown of the analysis. Some of these problems should be pointed out and discussed in the following in more detail.

5.1 Geometry and spatial discretisation

The primary problem is probably the very complex geometry of the human body, which is entirely unsymmetrical and uneven (cf. Fig. 6 for some examples). Here, dummy models often show a very simplified geometry, where external and internal surfaces have been smoothed considerably. The uneven geometry of the human models however has to be captured properly by the finite element discretisation. Since the mesh is strongly desired to consist of linear hexahedral and quadrilateral elements, the meshing process becomes fairly complex and partially, coarse meshed, very distorted and non-regular elements might occur, even in the undeformed state. In case of fully integrated elements, where eight and four integration points are distributed within each volume and shell element, respectively, large deformations and thus deviations of the element from the standard shape might lead to very small partial element volumes which decrease the accuracy of the finite element approximation considerably. Therefore, preferentially reduced integrated elements and a proper hourglass control are used, where the finite element equations are only evaluated in the element centre. These elements are also more suitable to capture large deformations of, for instance, the soft materials or the organs and they are not so vulnerable against element inversions.

Finally, these coarse and irregular meshes may also lead to very unsmooth and angular contact surfaces. This additionally makes high demands to the numerical algorithms and often numerical and algorithmic problems and instabilities can occur.

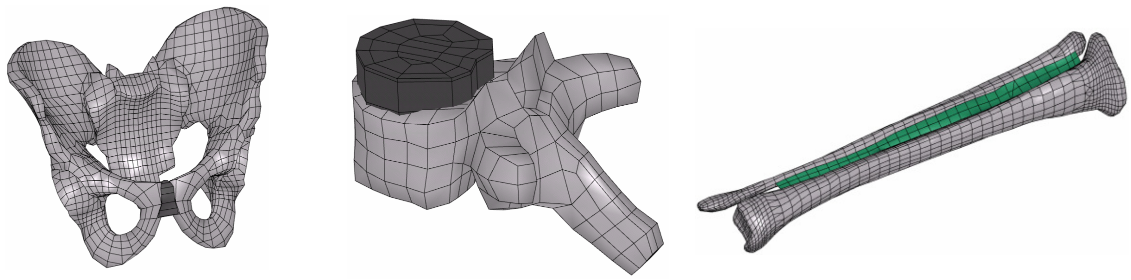

Figure 6: Details of the hipbone, the vertebra and the lower leg bone

5.2 Joint Modelling

The modelling of realistic joints is another special aspect of human models and differs considerably from the joint modelling in dummy models. A realistic modelling is crucial to represent a realistic relative motion of the model parts and to get reliable predications of possible injuries. In addition, these joints are often severely injured in a crash situation. However, the modelling of realistic joints makes again high demands to the numerical algorithms, since a multi-body contact between the bones, the meniscus (cf. knee joint, Fig. 5 or Fig. 7) and various ligaments has to be captured properly. Additionally the friction between the different joint parts and the connections to the surrounding flesh has to be taken into account. Considering again the rather complex geometry, consisting of curved and mainly non-smooth surfaces, inherited from the joint geometry, the contact conditions are often not captured satisfactorily and the penalty forces, applied to the penetrating slave nodes may again cause numerical instabilities and problems.

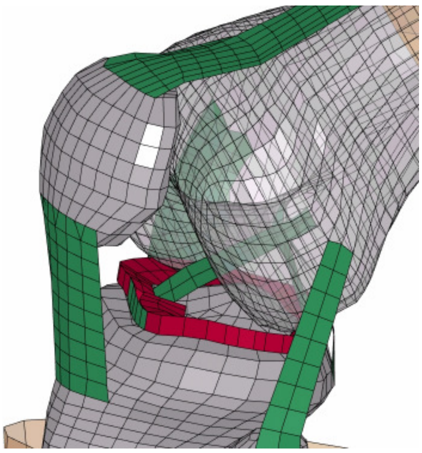

Figure 7: Details of the knee joint

5.3 Contact and tie contact conditions

Due to the complex geometry of the human body, single model parts are often meshed solitary and connected using tied contact conditions. Some examples are shown in Fig. 8, where firstly the transition from the abdominal (green) to the pulmonary area (red) is depicted and secondly the connection of the arm or leg bones to the surrounding flesh, where an additional shell layer is used and tied to the bone parts to realise a firm connection.

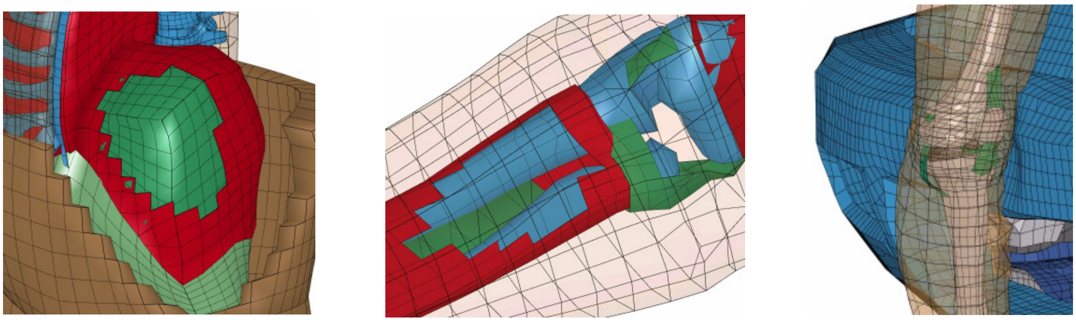

Figure 8: Connection of (left:) abdominal and pulmonary areas; (centre:) arm-bones to surrounding flesh and (right:) contact between THUMS and vehicle

Generally, constrained- or penalty-based tie formulations can be applied. While the penalty-based formulation computes a penalty force, according to the material stiffness or the maximum time step size and the distance change of the corresponding surfaces, the constrained-based formulation interpolates the accelerations of the master surface to the slave nodes. However, the computed penalty forces in the penalty-based method might be over- or underestimated, especially in case of materials of different stiffness. This can lead to non-physical oscillations in the interface, which are amplified during the calculation and eventually may lead to inverting elements and to an erroneous termination of the simulation. In addition, initial edge penetrations can amplify this effect. In this case, the constrained-based methods might be more stable, where by default, the slave nodes are first projected onto the master surface.

Over- or underestimated penalty forces can also occur in the global contact condition between the THUMS model and the vehicle, where entirely different materials interact (Fig. 8 - right). The materials of the vehicle are usually much stiffer than the soft flesh materials of the human model and special care has to be taken of how the contact is defined. Another example for this problem is for instance the contact conditions between the relatively stiff ribs and the internal organs. In addition to wrongly computed penalty forces, these contact situations can always cause very large deformations within the softer materials and possibly a self-inversion of these elements.

5.4 Actions and Possibilities to fix or avoid such Problems

Generally, it is not possible to avoid all numerical instabilities. Depending on the crash situation, the models have to be revised, contact or material parameters have to be adjusted and sometimes even the mesh has to be altered. However, most problems can sometimes be reduced using careful modelling techniques.

Because of the relatively coarse mesh, it is always a good idea to smooth or refine the mesh locally, especially in areas, where large deformations occur. This leads to a better resolution of the geometry, the surfaces are smoothed and the large deformations are better represented. Another aspect is the check of the contact conditions, where firstly initial edge or surface penetrations should be corrected (incl. penalty-based TIED-contact conditions). Additionally, contact parameters, like the penalty stiffness or the contact thickness can be adjusted to get a more stable contact condition. The contact partners are often defined using part-based surface definitions. Here difficulties may arise especially for the tied contact conditions, where unwanted constraints may occur. In any case, the contact partners should be defined carefully and cleanly using nodes or elements sets. One more aspect is that the THUMS model incorporates many rigid-body connections, where different model parts are connected using nodal constraints. The internal organs are for instance connected to the spine by associating nodes from the organs to rigid bodies within the spine. These connections can apply very large discrete forces to the soft internal organs which might again lead to severely distorted elements.

Here, attention should be paid on a sufficient distribution of these loads to the tied model part, i.e. multiple nodes should be used to transfer the loads to the softer materials.

6 Applications

In the following, some application examples are briefly presented, where the THUMS pedestrian and occupant models have been used in different crash and accident situations.

6.1 Occupant Safety – Sled test using the THUMS model

Possibly one of the first applications in Germany was performed by DaimlerChrylser AG in 2004 [6], where the AM50-THUMS was positioned in a sled to investigate the behaviour of the THUMS model in comparison to the Hybrid III dummy model.

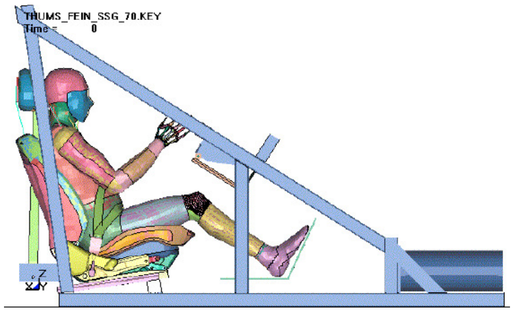

Figure 9: AM50-THUMS in sled test situation

The model was strapped to the sled (Fig. 9) and subjected to a deceleration, as, for instance, might occur in a frontal crash situation. In this situation, severe knee injuries can occur even at lower speeds, when the knee impacts the instrument panel. Therefore, the goals of this simulation were the assessment of the belt actions on the occupant and the investigation of possible injuries, arising from the knee contact with the dashboard. To be able to check for injuries, the model had to be refined in the lower leg region, i.e. the knee area as well as the upper and lower legs. The motion of the THUMS model during the deceleration is depicted in Fig. 10. Further information about the problem-specific results can be obtained from [6].

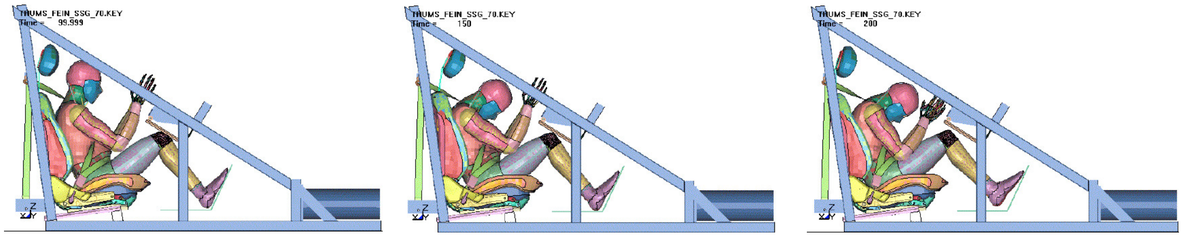

Figure 10: Motion of the AM50-THUMS model during the simulation

One important observation from the numerical point of view was the sufficient stable behaviour of the THUMS model during the simulation. Additionally, it turned out that the movement of the human model was far more supple and flexible, compared to the dummy model. The fairly loose joints enabled a better representation of the body motion during the crash and thus the credibility of the results was increased. However, this led to different results, where for instance the loading of the dashboard was considerably different between the two models.

6.2 Pedestrian Safety – pedestrian crash tests

The second example represents a typical application in pedestrian safety investigations. The AM50 pedestrian THUMS model is frontally hit by a deformable vehicle (Geo Metro, freely available from [9]).

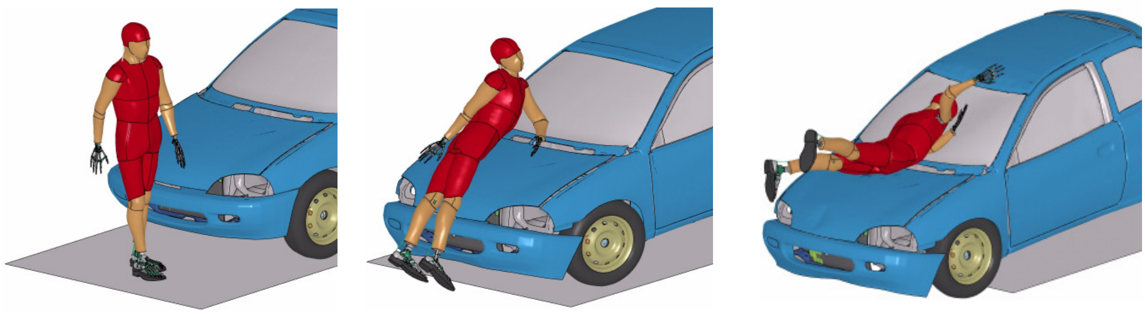

Figure 11: Typical pedestrian accident situation with the THUMS-AM50 model (v = 32km/h)

In this case, a vehicle speed of *32* and *56km/h* was taken into account. The motion sequence during the crash at 32km/h is depicted in Fig. 11. Additionally, Fig. 12 shows the final phase of the impact for the 6YO and the AF05 models.

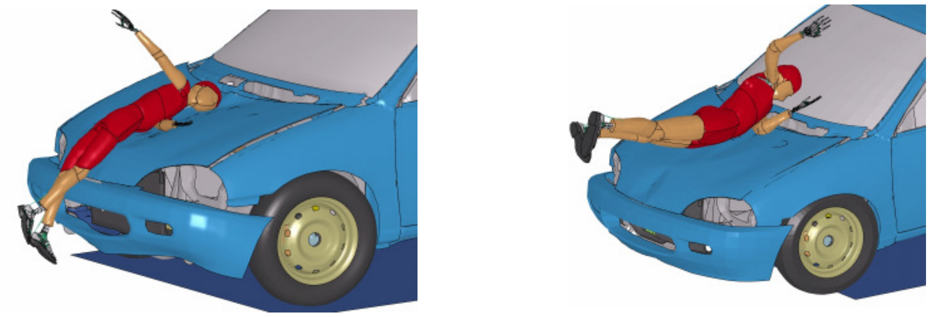

Figure 12: Impact of (left:) the 6YO THUMS model (56km/h) and (right) the AF05 model (32km/h)

While the three models AM50, AF05 and 6YO generally show a very different behaviour, the kinematics are fairly similar. However, the impact speeds and areas, where the models hit the vehicle, differ considerably, according to the respective model sizes. Additionally, obvious injuries, like bone fractures or tearing of ligaments can be observed, as is depicted in Fig. 13, where the initial impact of the vehicle to the three THUMS models is shown. While the primary injuries of the AM50 model are located in the lower legs (fracture of the tibia bone), the AF05 and the 6YO models show injuries in the knee (tearing of ligaments) and the upper leg (fracture of the femoral bone), respectively. However, the bone fracture predictions should be taken with care. The fracture is modelled, based on a maximum plastic strain, where the corresponding elements exceeding this strain are deleted from the model. Due to the very rough discretisation in these areas, the mass (and stiffness) removed by the element deletion process is generally overestimated and the model behaviour behaves far too soft, especially, since no possible post-fracture stiffness is considered.

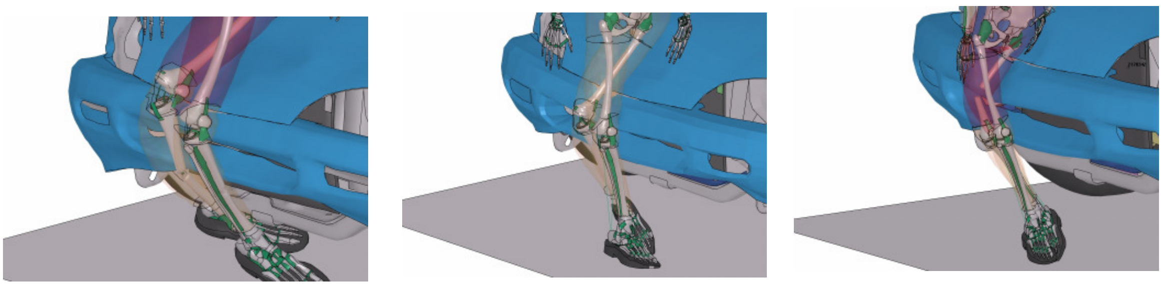

Figure 13: Tearing of ligaments and bone fractures for the (left:) AM50, (center:) AF05 and (right:) 6YO models at v = 56km/h

The principal goal of this kind of crash simulations is the investigation and control of the pedestrian kinematics during the crash. This includes the determination of impact velocities of the THUMS model and the localisation of the impact areas on the engine bonnet or the windscreen which are required to fulfil the current regulations and requirements of the pedestrian protection directives (e.g. *Euro NCAP* or *EC directives*). Additionally, the acceleration of the head during the impact phase is of high importance to derive possible head injuries of the pedestrian. This gives more insight into the general physics and the event of a crash situation and enables an improved development of passive and active safety systems.

6.3 Occupant Safety – Testing a seatbelt system

In a final example, the occupant AM50-THUMS model was used to test a special seat-belt attachment system, where the maximum force in the belt was controlled by a special mechanical system. In this example, the *AM50-THUMS* occupant model was again strapped to a seat model (see Fig. 14), which was kindly provided by *DaimlerChrysler AG*. Note that the presented seatbelt system was designed for a system without an airbag, like for instance the rear seat of a vehicle.

The simulation was then carried out by subjecting the subsystem to a prescribed acceleration and a maximum peak value of up to *40g* ≈ *390m/s*^{2}, as might occur in a typical frontal impact situation. The simulation with a total simulation time of about *140ms* was performed on a 4CPU Linux cluster using the LSDYNA MPP971 version and took approximately *12h*. The resulting motion sequence of the process is depicted in Fig. 15.

Figure 14: AM50-THUMS in seat model (courtesy of DaimlerChrysler AG)

In the first variant, the upper belt attachment was fixed to the B-column of the vehicle, i.e. fixed to a reference node of the subsystem. However, in case of a real accident situation, the seat-belt forces, especially in the shoulder belt, can be rather high and internal, as well as external injuries can easily occur. Therefore, a second variant was simulated, where the seat-belt was attached to the B-column using a special spring system which was able to control the maximum belt force, according to a chosen spring stiffness. The simulations showed considerable differences in the belt forces, especially in the shoulder belt, as can be seen in Fig. 16.

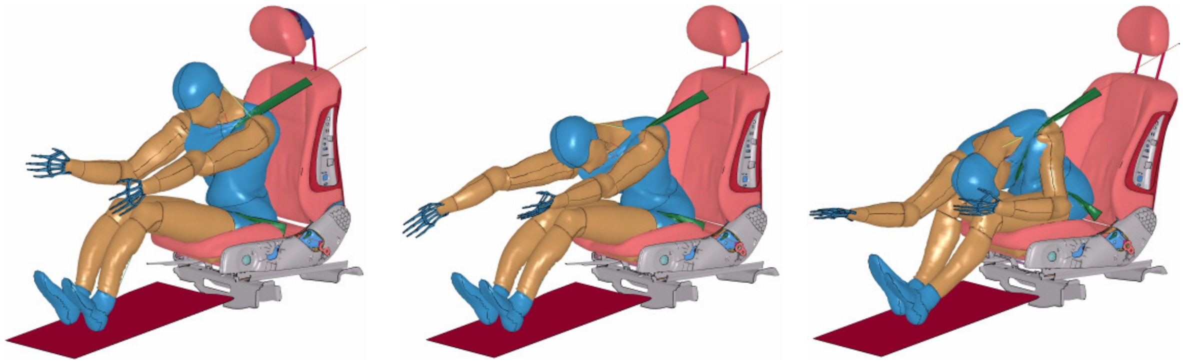

Figure 15: Motion sequence of the AM50-THUMS occupant model

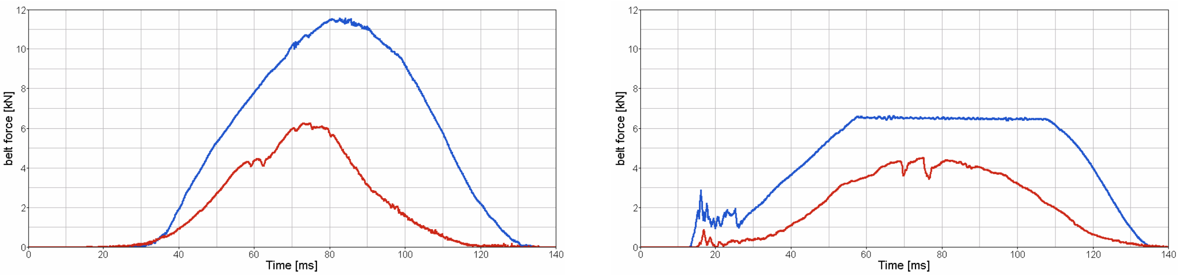

Figure 16: Belt forces in the shoulder and lap belt; (left:) fixed belt attachment and (right:) force-controlled belt attachment

The numerical behaviour of the THUMS model during the simulation was again quite stable and the termination time was reached in almost all performed simulations. However, difficulties occurred in those areas, where the belt cut into the softer parts of the human model, especially in the neck area (shoulder belt) and the abdominal area (lap belt – Fig. 17). Due to the extreme stiffness differences of the internal organs and the surrounding bones or external model parts, this is generally a very problematic area of the THUMS model and special care has to be taken to avoid severely distorted or even inverted elements.

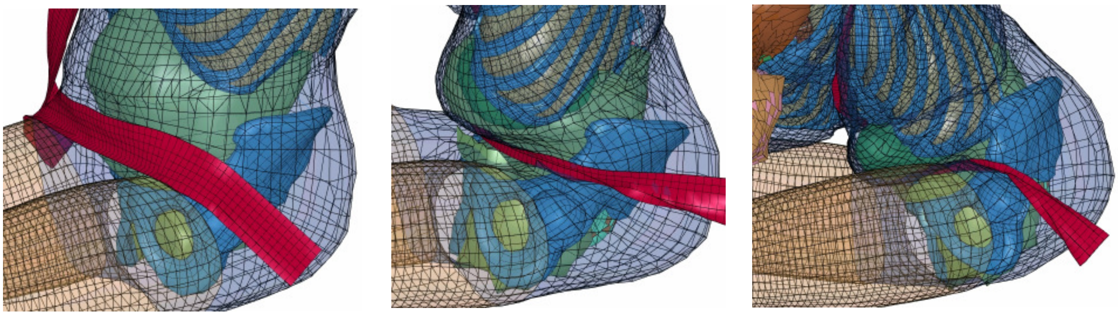

Figure 17: Deformation of the abdominal area during the simulation

7 Summary & Conclusions

Generally, the expectations concerning human modelling are currently very high. The first fairly detailed models exist and the first applications using the THUMS model are on the way and already showed some usable and very promising results. However, the numerical stability is still hard to achieve with these models and a meaningful mesh refinement in almost all model areas is advisable to increase the accuracy and reliability of the results. On the other side, this process requires much time and work and additionally increases the computational effort.

As a conclusion of the first tests, e.g. the example in Section 5.3, the handling of very large local deformations of single model parts is still a challenging problem. If local mesh refinements are not realisable, internal contact conditions might be a workaround to capture these deformations without element inversions. This can either be done using the *CONTACT_INTERIOR contact card of LS-DYNA, which experientially works very well in moderate cases or in more severe situations, internal contact shells, i.e. contact shells on each element face, have to be used in a *CONTACT_AUTOMATIC_SINGLE_SURFACE definition. In future models, these deformations could also be resolved using meshless methods locally, e.g. the EFG method.

The additional detailing of the model is an inevitable requirement for the human models. This includes for instance the consideration of muscle activities, which might lead to a shift of the model stiffness distribution and will thus have a considerable influence on the results. This is currently under heavy development and multiple submodels of single body parts exists. The inclusion into one holistic model and the corresponding model validation however hasn't been done yet. On the other side, the inclusion of single internal organs to increase the possibilities for injury predictions, especially in the abdominal and pulmonary areas is already on the way (see e.g. [4]) and corresponding models will be available in the near future.

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