COMPUTATIONAL HUMAN BODY MODELS

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Abstract. Computational human body models are widely used for automotive crash-safety research and design and as such have significantly contributed to a reduction of traffic injuries and fatalities. Currently crash simulations are mainly performed using models based on crash-dummies. However crash dummies differ significantly from the real human body and moreover crash dummies are only available for a limited set of body sizes. Models of the real human body offer some promising advantages including the prediction of injury mechanisms and injury criteria. In this paper, a review will be given of a number of developments in the field of occupant crash simulations in the past 40 years. Topics presented include history of occupant crash simulation codes, human body geometry, human body material modelling and model quality rating. A discussion on foreseen future developments in this field will conclude this paper.

Keywords: Vehicle safety, injury biomechanics, simulation models, vehicle design

1. INTRODUCTION AND HISTORICAL REVIEW

In the crash safety field, mathematical models can be applied in practically all area's of research and development including:

- design (CAD) of the crash response of vehicles, safety devices and roadside facilities

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- reconstruction of actual accidents
- human impact biomechanics studies

Dependent on the nature of the problem, several types of crash analysis programs have been developed each with their own, but often overlapping, area of applicability. Most of the models are of the deterministic type, that is, based upon measured or estimated parameter values, representing “average” characteristics of the human body, safety devices, the vehicle and its surroundings and using well established physical laws, the outcome of the crash event is predicted. Although the various deterministic models may differ in many aspects, they are all dynamic models. They account for inertial effects by somehow deriving equations of motions for all movable parts and solve these equations by a numerical method. The mathematical formulations used for these models can be subdivided into lumped mass models, multi-body models and finite element models. In a lumped mass model a system is represented by one or more rigid elements often connected by mass-less elements like springs and dampers. An example of a lumped-mass model in human body modelling is the well-known one-dimensional model of the human thorax developed by Lobdell in 1973 [**1**]. This model simulates the thorax response in case of a loading by an impactor. The model consists of 3 rigid bodies connected by springs and dampers. One mass represents the impactor mass and other masses the sternal and vertebral effective mass, respectively. Springs and dampers represent the skin and flesh between impactor and sternum and the connection between sternum and thoracic spine. The response of this model was shown to correlate well with post mortom human subject tests, further referred here to as PMHS tests.

1.1 Multi-body models

The most important difference between a lumped mass model and a multi-body model is that bodies in a multi-body formulation can be connected by various joint types, due to which the number of degrees of freedom between the elements can be constrained. A lumped mass model in fact can be considered as a special case of the more general multi-body model formulation. External forces generated by so-called force-interaction models cause the motion of the joint-connected bodies in a multi-body model. Examples of force-interaction models in a multi-body model for crash analyses are the model that accounts for an acceleration field, spring-damper elements, restraint system models and contact models. Another difference with lumped mass models is that in a multi-body formulation, instead of rigid bodies, also flexible bodies can be specified. Multi-body models in which the complete human body is simulated for the purpose of crash analyses are often referred to as Crash Victim Simulation (CVS) models, human body gross-motion simulators or whole body response models.

One of the early human CVS models, illustrated in Figure 1, was developed already more than 40 years ago by McHenry [**2**]. The model that represents the human body together with restraint system and vehicle is 2-dimensional and has 7 degrees of freedom. Mc.Henry compared his model calculations with experimental data and was able to show quite good agreement for quantities like hip displacements, chest acceleration and belt loads.

The results of this model were so encouraging that since then several, more sophisticated, models have been developed. The most well known are the two-dimensional 8-body MVMA-2D [**3**], the three-dimensional CAL3D allowing up to 20 elements [**4**] and MADYMO 2D/3D allowing an arbitrary number of bodies, both rigid and flexible ones and a range of joint types [**5**]. For a review of the status of these models at the end of the eighties the reader is referred to Prasad and Chou [**6**].

MADYMO, which is developed and supported by TNO Automotive in the Netherlands, has since then gone through an extensive further development and validation program and includes among others a finite element part for crash analyses. The multi-body module of MADYMO calculates the contribution of the inertia of bodies to the equations of motion; the other modules calculate the contribution of specific force elements such as springs, dampers, muscles, interior contacts and restraint systems. Special models are available for vehicle dynamic applications including tyre models and a control module offers the possibility to apply loads to bodies based on information extracted from sensors.

Apart from MADYMO above models are hardly used anymore nowadays. One exception is a special version of the CAL3D program called the ATB (Articulated Total Body) program developed by the Air Force Aerospace Medical Research Laboratory in Dayton [**7**] for aircraft safety applications.

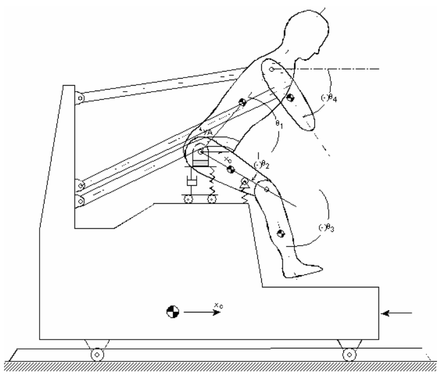

Figure 1. Example of a two-dimensional multi-body model by Mc.Henry [**2**].

1.2 Finite element models

The finite element method is a numerical technique to solve equilibrium equations for a domain with arbitrary shape and constitutive properties. In a finite element model the system to be modelled is divided in a number of finite volumes, surfaces or lines. These elements are interconnected at a discrete number of points: the nodes to which degrees of freedom are associated. In the displacement-based finite element formulation, which is applied in practically all major finite element software packages, the motion of the points within each finite element is defined as a function of the motion of the nodes. The state of stress follows from the deformations and the constitutive properties of the material modelled. One of the earlier examples of using the finite element method for human body impact modelling is a model of the human head developed in the seventies by Shugar [**8**] and included a representation of the skull and brain. Linear elastic and linear visco-elastic material behaviour was assumed. The skull bone response and the brain response from the model were compared with experimental results of head impact tests with primates.

Three of the currently most often used software packages for crash simulation using the finite element method are LSDYNA 3D, RADIOSS and PAMCRASH. These packages are based on the public domain version of the DYNA explicit finite element program that was developed at the Lawrence Livermore Laboratories during the seventies [**9**]. For the spatial discretization, the available elements include shell elements, solid elements, beam elements and membrane elements. A large number of material models are available, among others, describing elastic material behaviour, elastic-plastic material behaviour with isotropic hardening and failure, crushable foam with failure, orthotropic material behaviour and strain rate dependent material behaviour.

1.3 Hybrid modelling

The above finite element crash codes allow the inclusion of rigid bodies and are able to simulate some of the specific features of multi-body crash simulation programs. In the MADYMO crash simulation program that originally was developed as a multi-body code, most of the capabilities of the finite element based crash codes are provided in the integrated FE module. Moreover external interfaces between MADYMO and the FE based crash codes are available allowing integrated multi-body finite element simulations further referred to as hybrid simulations. An early example in which both the multi-body approach and the finite element approach are used in an integrated approach is the model of a car occupant interacting with a passenger airbag developed in the eighties by Bruijs [**10**]. The airbag (and airbag straps) was modelled in the PISCES 3D-ELK program (now MSC-DYTRAN) using almost 2000 triangular membrane elements. The finite element airbag model interacts with a multi-body model of the Hybrid III crash dummy modelled in MADYMO 3D.

2. HUMAN BODY MODELLING

2.1 Introduction

Human body models for crash analyses can be subdivided into models of crash dummies and models of the real human body. For a long time the focus has been on crash dummy modeling due to the need, particularly from the design departments in the automotive industry, for well-validated design tools which can reduce the number of regulatory tests with crash dummies in order to shorten and optimize the development process of a new car model and its safety features. Most model input data in case of crash dummy models can be measured relatively easily and moreover, results of experiments with crash dummies often are available for model validation and if not, such experiments, unlike tests with biological models, readily can be carried out in a well-equipped crash laboratory.

The need for well-validated databases of crash dummies has been recognised by many organisations in the past and has resulted in a number of (co-operative) research efforts to develop such databases. A detailed presentation of these efforts would be out of the scope of this paper, however worthwhile to mention here is the first effort of this kind in the mid-eighties concerning the Hybrid III crash dummy. Prasad [**11**] conducted in 1985 a series of frontal sled tests using a Hybrid III dummy on a rigid seat at 3 different severity levels. The test results were available for a SAE (Society of Automotive Engineers) subcommittee for the purpose of validation of dummy databases of the ATB and MADYMO programs. These validation efforts were presented at the 1988 SAE congress by several authors [see e.g. **12**], which resulted in a number of recommendations for further improvement of the quality of the Hybrid III dummy model database.

For most of the current crash dummies, nowadays, databases (often well-validated) for the various crash codes are available and continuous activities take place in various organisations and user groups to further improve such databases as well as to develop databases for new crash dummies.

This paper will focus further on models of the real human body. A model of the real human body is much more difficult to develop than a model of a physical crash dummy. This type of models offers improved biofidelity (human-likeness) compared to crash dummy models and allows the study of aspects like body size, body posture, muscular activity and post fracture response. Furthermore they potentially allow analysis of injury mechanisms on a material level. In the next sections, several important aspects of human body models will be discussed namely how to deal with the human body geometry (anthropometry), modelling of human body material and validation of human body models.

2.2 Anthropometry

One of the challenges in modelling the real human body compared to crash dummy modelling is how to deal with the large variations in human body sizes that exists. In case of a multi-body approximation several methods exist allowing the generation of an arbitrary sized human body model. Two of the most widely used methods will be mentioned here. The first one was developed in the early eighties and is available through the software package GEBOD [**13**]. This software generates geometric and inertia properties for a 15 segment ATB or MADYMO multi-body model. Computations for the geometrical parameters and mass distribution are based on a set of 32 body measurements to be specified by the user or generated by GEBOD using regression equations on the basis of body height and/or weight for both adult males and females. Also for children, regression equations are available. A major limitation of GEBOD is the approximation of body segments by simple geometrical volumes.

The second method is based on the use of software packages for ergonomic analyses like the RAMSIS software [**14**]. The RAMSIS model describes the human body as a set of rigid bodies connected by kinematic joints and the skin is described as a triangulated surface. RAMSIS provides a detailed geometric description of the body segments based on extensive anthropometric measurements on various civilian populations including automotive seated postures. In RAMSIS the body dimensions of each individual can be classified according to three dominant and independent features: body height, the amount of body fat, and body proportion, i.e. the ratio of the length of the limbs to the length of the trunk. A translator has been developed to convert RAMSIS models into MADYMO models [**15**]. The resulting database contains joint locations, joint ranges of motion, segment masses and centres of gravity and a triangulated skin connected to various body segments. This human model has been extended to a full dynamic human model suitable for simulation of impact and vibration loading [**15**].

The methodology available through RAMSIS can also be applied to scale crash dummies. Happee [**16**] created 30 different models by scaling male and female Hybrid III dummy models towards various RAMSIS anthropometries for the purpose of evaluation of restraint systems in a frontal collision mode. The models accounted for human variance with respect to length, corpulence and the proportion of seated height to standing height.

For detailed finite element based human body models the anthropometric information provided by RAMSIS is much too global. Detailed information is needed on the structures within the human body. One of the efforts to achieve this information for a specific subject is the work done in the European HUMOS-1 project [**17**]. For this purpose the method of physical slicing of a PMHS in driving position was chosen. The slices were photographed and afterwards digitised. The resulting MADYMO model from this HUMOS-1 project is illustrated in Figure 2.

The PMHS measured in HUMOS-1 approximated a 50th percentile human male. Alternative methods to achieve the detailed human body anthropometry are based on MRI techniques. A limitation of these models, although they are very detailed, is that they represent one unique human body size namely the one PMHS that was actually measured.

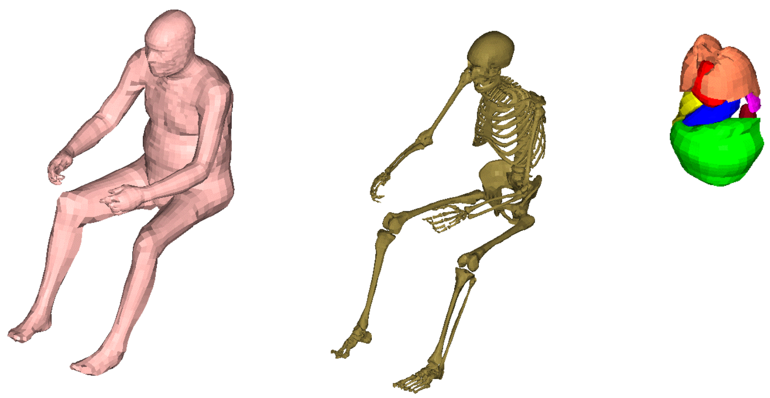

Figure 2. MADYMO Finite Element Occupant Model in automotive seating position. (soft tissues-left; skeleton-middle, organs-right)

2.3 Material modelling

Simulations with human body finite element models require constitutive descriptions for the various materials that constitute the human body (such as bone, cartilage, ligament and tendon, muscular tissue, and various organs such as brain, heart, lung, etc.). Accurate representations of the mechanical behaviour of the various components are essential for reliable predictions of injury in impact situations.

In general, properties of biological tissues are visco-elastic (i.e. their response is rate-dependent and they show stress relaxation at constant strain level), non-linear, and anisotropic due to the specific microstructure (for example consisting of an arrangement of collagen fibres). A full characterisation of the constitutive behaviour considers the behaviour in various deformation modes (shear, uni-axial tension, compression, bi-axial deformation, etc.) and complex loading paths (e.g. reverse loading). Furthermore, the use of constitutive models for biological materials in impact biomechanics simulations requires a characterisation of these materials at high strain rates. The visco-elastic characteristics are typically determined in (small strain) oscillatory experiments, stress relaxation experiments, and constant strain rate tests at varying strain rates. Prior to the characterisation experiments, specimens are often preconditioned. The frequency range or stain rates that can be addressed is often limited by the capabilities of the experimental set-up. Characterisation experiments are often conducted *in-vitro*, on small specimens, either in compression/extension or, more commonly, in shear [**18**]. *In-vivo* experiments are sometimes carried out by indentation of organs [**19**].

The mechanical properties of living tissues may depend on age and gender. Furthermore, properties vary largely between different subjects. Therefore, mechanical experiments on biological materials show a large scatter in obtained results. Additional scatter in data is due to varying test conditions (both physical and mechanical), handling and treatment, and post-mortem time (since most tests are conducted *in-vitro*). Furthermore, regional differences within an organ or within the body may exist. Tests are conducted either on human cadaveric material or on tissues from animal donors. The advantage of the latter is that material can often be tested at shorter post-mortem times or even in vivo. Consequently, the properties of biological materials as reported in the literature vary widely. For example, the mechanical properties reported for brain tissue vary over an order of magnitude. An overview of mechanical properties of various biological materials is given in [**17**].

The mechanical behaviour of biological tissue is the result of the properties of the individual microstructural components that constitute the material (for example collagen fibres and surrounding matrix material) and the interplay between these components. For soft tissues, often hyperelastic models are applied, which represent true elastic behaviour. Hyperelastic constitutive laws can be derived from a strain energy function. This energy function is given in terms of the deformation gradient tensor, often through invariants of the Cauchy-Green strain tensor. The strain energy function must be chosen such that the obtained constitutive relation matches experimental data. Some common choices for a hyperelastic model are for example the Mooney-Rivlin model or the Ogden model. Although isotropic models are successfully used for many applications, the incorporation of anisotropy in constitutive models can be essential. For soft tissues, a fiber-reinforced model may be used, where the strain energy function depends on the fiber stretch. Orthotropic elasticity is sometimes used for anisotropic materials such as bone [**20**].

A viscoelastic material model can be represented by a mechanical analogon consisting of a certain arrangement of springs and dashpots. By placing a number of so-called Maxwell elements in parallel, a general viscoelastic framework can be obtained. The linear viscoelastic theory considers the concepts of proportionality and superposition. In this theory, an arbitrary loading-history is assumed to be given by a Boltzmann integral over an infinite number of small steps. The so-called quasi linear viscoelastic (QLV) theory has been proposed by Fung [**21**]. This theory has become widely used in injury biomechanics and has been successfully applied for the constitutive or structural modelling of many soft biological tissues [**22**]. The QLV theory is a generalisation of the linear viscoelastic theory and is also formulated in terms of a convolution integral. In this integral representation, the elastic response is separated from the relaxation function. The quasi-linear viscoelastic theory assumes the time-dependent behaviour to be linear and a non-linear relation for the instantaneous elastic response can be used. This instantaneous elastic response is commonly derived from a strain energy function.

The properties of skeletal muscles can be separated in an active and a passive component. The active response may become important in low speed accidents such as for example rear-end collisions producing whiplash disorders [**28**]. One-dimensional phenomenological models are often used to describe the response of skeletal muscles. The Hill muscle model [**23**] is frequently used for bar elements that simulate the active and passive response of skeletal muscles.

Injury will develop if the mechanical response (e.g. strains, stresses, etc.) of the biological material attains a level at which either the structural integrity of the materials is affected or functionality is reduced. The latter may be the result of physiological processes that occur after the impact, at time scales that are much larger than the time scale of the loading conditions.

2.4 Validation

Validation is the process of assessing the reliability of a simulation model in comparison to one or more reference tests with human subjects. Very important in this process is that the reference tests, often also referred to in literature as biofidelity tests, are not the same tests as used for determinination of model input data. If results from different tests are available, usually so-called biofidelity corridors are defined for instance consisting of envelopes of resulting time histories.

Human models have been validated for frontal, lateral, and rear impact as well as pedestrian loading [e.g. **15, 17, 28, 29**] using volunteer tests for low severity loading and PMHS tests for higher severity loading. Recently the validity range of the MADYMO multibody human model has been extended to vertical vibration transmission [**27**].

FE human models have also been validated using bone segment testing [**17**] and some progress validating soft tissue responses has been made using marker and ultrasound techniques.

While human models have been validated extensively for kinematics, accelerations and for compliance (force-deflection) the next step is to demonstrate injury prediction capabilities of human body models which is an area still in its infancy. Some promising results in this respect have been achieved, among others, for long bones where initiation of bone failure was predicted based on yield stress and plastic strain [**26**].

3. DISCUSSION AND CONCLUSIONS

A general advantage of computer crash simulations over crash tests with mechanical human substitutes (crash dummies) is that the safety performance of design concepts and the effect of changes in the design can be studied efficiently, sometimes even without a prototype to be built (virtual testing). An important condition for virtual testing is that well-validated databases of the human body are available. Continuous efforts are needed to further improve the quality of models in order to allow their usage in even a wider range of applications and as assessment tools in crash regulations. Standards for validation procedures and performance criteria are needed for this purpose. In the past some attempts have taken place to develop such standards, for instance, the Validation Index developed in the early eighties by the "Analytical Human Simulation Task Force" of the SAE Human Biomechanics and Simulation Subcommittee (HBSS) [**24**]. A range of methods to generate objective rating methods for the quality of crash models has been evaluated within the European project VITES. As a results of this project the analysis tool called ADVISER has been developed that can assist the user/developers of crash models in assessing the quality of their models in an objective manner [**25**]. In addition the ADVISER stochastic tool enables prediction of the stochastic response of crash tests in relation to the scatter of the component responses in the system.

The earliest numerical models of the full human body have been based on multibody techniques. More recently also finite element techniques have been used for this purpose. A major advantage of the multibody approach is its capability of simulating, in an efficient way, spatial motions of mechanical systems with complex kinematic connections like they are present in the human body and in parts of the vehicle structure. The advantage of the finite element method is the capability of describing (local) structural deformations and stresses in a realistic way. But the creation of a finite element model is a time consuming job and the availability of realistic material data is still limited. Furthermore relatively large computer times are required to perform a finite element crash simulation, making the method less attractive for complex optimisation studies involving many design parameters or for stochastic type of simulations.

Models of the human body can be subdivided into models of crash dummies and models of the real human body. Many models of crash dummies have been developed and extensive series of validation studies have been conducted with rather impressive results. Also in the field of real human body models rather promising results have been achieved. An important advantage of real human body models is that they allow the study of the effect of body size, posture influence as well as muscular activity. The advantage of a design strategy based on real human body crash models over a design strategy based on crash tests with dummies (and crash dummy models) is the possibility to benefit without delay, in principle, from new scientific knowledge on injury mechanisms and injury criteria obtained through biomechanical research. In case of a crash test dummy based design strategy usually a long period elapses before new findings actually can be implemented in crash dummy hardware.

Several areas can be identified in the field of real human body models where further developments should take place. This includes further improvements in the description of the non-linear dynamic behaviour of muscles (incl. neuro-muscular control), the modelling of complex human joints and the study of constitutive equations and parameters for biological materials (e.g. brain, skin). The development of constitutive models that consider the behaviour in various deformation modes and complex loading paths remains a challenge.

Other areas of developments include detailed finite element models that fully take into account anthropometry and age variations over the population, like already is possible now to some extent in case of global multi-body based human body models. Also there is a clear need for models that account for the pre-crash response of the human body in view of development of pre-crash sensing based restraint systems.

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