Modelling of impact on the head-neck complex

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Modelling of Impact on the Head-Neck Complex:

Report on a research program
supported by a Ford Motor Company grant (1996-1997)

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1. Introduction

In 1990 a new research field was defined at the Eindhoven University of Technology, in the field of injury biomechanics. This research field was positioned in the Department of Computational and Experimental Mechanics of the Faculty of Mechanical Engineering. The main reason for this was that this department had already a long-lasting research experience in the field of general biomechanics and the availability of a well-equipped laboratory for mechanical testing (Annex A). The department participates also in the Dutch Research School of Engineering Mechanics.

To make students familiar with the field of injury biomechanics a special course "Introduction in Injury Biomechanics" was developed dealing with topics like epidemiology of traffic injuries, injury mechanisms and injury criteria, biomechanics of head, neck, thorax and lower extremities, crash dummies and computer modelling as well as injury prevention strategies. This course was attended by more than 200 students. More than 60 students carried out 3-month or 9-month research projects (Master Degree) and several PhD projects were finalised. A number of the students have found positions in European industries and research institutes working in the field of vehicle safety.

Head and neck injuries were selected as the primary area of research due to the large contribution of these injuries to the traffic injury problem. The various research projects in the field of injury biomechanics were funded by university grants and by several external organisations and institutions including The European Community, The Netherlands Technology Foundation STW and the Netherlands Organization for Applied Scientific Research (TNO). For 1996 Ford Motor Company awarded an unrestricted grant of $50,000 to support the research in the field of "Modelling of Impact on the Head-Neck Complex". Also for 1997 this award was granted.

The Ford grants were used to improve and expand the infrastructure of the Department of Computational and Experimental Mechanics. More specifically 3 high-end workstations were purchased to be used in various student projects dealing with computer modelling of the head and neck structure and the experimental facilities were expanded with a High Speed Motion Analysis system (Kodak Extarpo model 4540). This system will be used for the research of material properties of biological tissues and neck response during impact. Also several visits of students and staff to international conferences like the Stapp conference were made possible from the Ford grant.

To discuss the progress of the work several meetings with dr. Priya Prasad of Ford Motor Company, Dearborn USA were organised and results of research projects like PhD thesis reports and computer models were made available to Ford Motor Company. In this report a summary of the work in the past period is presented. Chapter 2 deals with head injury biomechanics and chapter 3 with neck injury biomechanics. Chapter 4 presents an outlook for the coming period.
2. Head Injury Biomechanics

2.1 Introduction

Impact loads on the head may lead to traumatic brain injury, generally classified as diffuse injury, focal injury, or injuries resulting from relative motion between brain and skull (subdural hematoma and brain stem injury). Knowledge on the mechanisms by which an impact load results in injury is still incomplete. Essential for our understanding of the injury mechanisms is knowledge of the regional load within the tissue, i.e. the load that is experienced by the axons, the blood vessels and the connective tissue. If (some unknown aspect of) this regional load exceeds a certain tolerance level of the tissue, damage will occur. Experimental assessment of regional load is virtually impossible, because of lack of suitable, non-destructive measuring techniques. Instead, numerical modelling may yield information on regional load.

The aim of the Head Injury Biomechanics Program at the Eindhoven University of Technology is to improve insight into the mechanisms through which an impact load on the head results into brain injury, and, eventually, to use this insight to set up guidelines for head protection measures. A two-step approach is followed. In the first step, the regional tissue load resulting from a global head impact load is determined through experimentally validated numerical models. For validation, the relation between global and regional load is studied experimentally in physical models, mimicking the human head. Next, injury mechanisms are studied by correlation of regional load with literature data on distribution of brain damage. Moreover, data from loading experiments on individual axons and blood vessels may be used. Finally, the numerical model will be used to predict brain damage from a given global load, and to evaluate possible head protection measures.

2.2 Completed research

In 1997, a PhD-thesis was completed, entitled “Finite element modelling of the human head under impact conditions” [1,3]. First, a literature survey of existing finite element models was conducted [2]. Then, based on CT and MRI data, a 3D finite element model of skull and brain was constructed, consisting of 1756 linear brick elements and 2257 nodes. Material properties of brain and skull were taken to be isotropic and linearly elastic, and no relative motion between brain and skull was allowed at their interface. The model was subjected to an impact load with the shape of a sine function, an amplitude of 7 kN and a duration of 10 ms. Predicted pressure-time histories showed trends, similar to published experimental data. Temporal and spatial discretisation was found to be sufficiently fine.
The model was used as a reference model, from which parametric variations were performed with respect to constitutive properties, boundary and interface conditions and anatomical detail. Variation of the Young's modulus was found to affect distributions of pressure and Von Mises stress significantly. Introduction of a linear viscoelastic brain constitutive model primarily affected Von Mises stress-time histories. Assuming a free interface between brain and skull reduced pressures typically by a factor three, while the magnitude of Von Mises stresses increased up to a factor two. Further addition of the foramen magnum had a minor influence on Von Mises stresses in the foramen region. Introduction the falx cerebri and the tentorium as linearly elastic structures with a stiffness 30 times higher as that of the bulk brain material, was found to affect primarily Von Mises stresses, while leaving pressures unchanged. Including the frontal sinus hardly affected the response of the model.

It was recommended to pay in the future investigations special attention to modelling of material properties and boundary conditions.

In parallel to the PhD-project, a two year post masters project was completed, in which the material properties of brain tissue were investigated [5]. Samples of calf brain tissue were subjected to harmonically varying torsional shear up to frequencies of 16 Hz. Up to strains of 1%, tissue behaviour could be considered linearly viscoelastic. Applicability of the time/temperature superposition principle was demonstrated, such that the results might be extended to higher shear rates [8]. Moreover, an experiment was designed, in which tissue can be subjected to more complex loading conditions. A cylinder, filled with gelatine mimicking brain tissue, was subjected to transient loading. The deformation field in the gelatine was both measured, and predicted using a finite element model in which initial estimates of the material parameters were used. Subsequently, best fit parameter values were determined by systematically minimising differences between computed and measured displacement fields [6].

Finally, in a series of masters projects, one- and two-dimensional wave propagation in elastic and viscoelastic solids was investigated, both experimentally and numerically [7, 9].
3. Neck Injury Biomechanics

3.1 Introduction

The incidence of neck injuries in traffic accidents appears to be relatively low compared to for instance head injuries, except for specific accident configurations like a rear end collision where more than 50% of the injuries appear to be in the neck area. The long-term consequences of neck injuries however are often very serious, even in case of "minor" injuries (so-called whiplash injuries). The IPR (Injury Priority Rating) which weighs motor vehicle injuries by body region in terms of total societal costs (see Table 3.5), rates neck injuries about 5% of the total IPR, which makes neck injuries the fifth most important injury category (after head, face, chest and abdomen).

Knowledge on the mechanism causing neck injuries is still rather limited and the aim of the Eindhoven University of Technology research in this field is to increase the knowledge on the injury mechanism by computer modelling of the neck structures on the basis of which improved methods for neck protection can be developed.

3.2 Completed research

The response of the human neck in impact conditions has been studied at Eindhoven University in several projects. In 1996 de Jager [13, 14] completed his PhD work. He developed two neck models; a global model and a detailed model. In the global model the effects of all structures limiting the intervertebral motion were simply described as resulting stiffness and damping models. In the detailed model, several ligaments were modelled geometrically, the facets joints were implemented and neck muscles were included. De Jager validated his models for frontal and lateral loading using NBDL volunteer data.

De Jager's simulations with active muscle behaviour indicated a relevant contribution of reflex induced activity. Moreover it was concluded that modelling the neck muscles as simple cords connecting origo and insertio was not satisfactory. For this reason van Haaster [10] enhanced the muscle model by defining curved muscles. He also implemented several smaller muscles omitted by de Jager. Van der Horst finalised the curved muscle model and published the results at the 1997 STAPP Conference [11].

Fig. 2 De Jager detailed neck model [14]
4. Current and Future Research

In 1997, a new PhD-project was started, entitled 'Dynamic behaviour of brain tissue under impact loading'. This project focuses on the characterisation of the constitutive behaviour under impact loading conditions and on the development of validated numerical methods to describe propagation of pressure and shear waves in nearly incompressible materials. For characterisation and validation, physical models of head and brain will be subjected to loading conditions, representative for impact. During development of the models, a gel, mimicking brain tissue, will be used.

In parallel to the PhD-project, brain injury mechanisms in animal tests will be investigated. In co-operation with Janssen Pharmaceutics Belgium, an apparatus is developed to be able to apply a well defined impact load to the head of a guinea pig. During impact, forces and kinematics will be measured. Post mortem, the spatial distribution of brain injury will be evaluated. These experimental data are considered of great value for partial validation of the numerical models of head mechanics, and for finding correlation between distributions of regional mechanical load and brain injury.

A second PhD project recently started in the field of head injuries dealing with the helmet as a protective device. Based on a preliminary FEM model of the helmet developed in a master student project [16] a research project has been defined in which it is intended to couple a brainmodel to a helmet model in order to study the effect of various helmet design parameters on head injury risk. Finally in a 2-year post-master project several of the current FEM brain models will be investigated for their suitability in accident reconstructions as part of a European research project.

![Fig. 3 Preliminary helmet model [16]](image_url)

In the field of neck injury biomechanics a new PhD project has started dealing with further validation and improvement of the 3-D de Jager neck model. Research will concentrate on muscle response. For this purpose low g-level volunteer tests will be conducted in co-operation with Maastricht Medical University. EMG, x-ray, and high-speed video measurements are part of the test protocol.

Finally it should be mentioned here that currently a facility is being set up in our laboratory to study the behaviour of muscle cells under a variety of mechanical loading conditions. It will be investigated whether this facility also can be used to study the response of nerve cells. In particular, the relation between mechanical load and damage on the cellular level can be investigated, which may yield insight into injury mechanisms.
REFERENCES


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Annex A Experimental facilities

The main usage of the experimental facilities of the department of Computational and Experimental Mechanics is the determination of mechanical properties of polymer materials in their solid state, as a melt, or in solution. To determine the desired properties two distinct approaches can be distinguished. Firstly, the standard methods. These involve tests on standard loading geometry's such as tensile tests, shear tests. To perform these experiments there are tensile testers (Frank-10kN, Zwick-10kN-20kN-250kN), miniature tensile testing (PL Minimat, SEM tensile stage), long term creep, falling weight impactor, rheometer (Rheometrics RDS2/RFS2), thermal analysis (DMTA PL MK III).

Secondly, the non-standard methods, involving tests on complex loading geometry's or inhomogeneous materials. These experiments are usually combined with sophisticated numerical techniques in so-called hybrid methods. Experimental equipment comprises amongst others: flow induced birefringence measurement, 3-D laser Doppler anemometry, contactless strain distribution measurement (Hentschel and SD800-ESPI-3D).

All these options are complemented by a large amount of central facilities such as e.g. workstations, modelling software, real time image acquisition and off-line image processing, data acquisition systems. Moreover, a workshop is at hand which can aid in any issue of mechanical or electrotechnical nature, either modifications, or completely new concepts.