UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A ONE-YEAR-OLD ASIAN DUMMY MODEL FOR FINITE ELEMENT PREDICTION OF INJURY IN AUTOMOTIVE CRASH

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By

MAI NURSHERIDA BINTI JALALUDDIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

TO:

MY DEAREST PARENTS;
ALLAHYARHAM HAJI JALALUDDIN BIN HAJI UDIN AND ALLAHYARHAMMAH HAJJAH SHARIPAH SAPIAH BINTI SYED HASSAN AL-JAMALULAIL.

MY HUSBAND;
MOHD ROSDAN BIN SULAIMAN.

MY DEAREST CHILDREN;
AISHAH UMAIRAH BINTI MOHD ROSDAN, AKID NAQIUDDIEN BIN MOHD ROSDAN, ASLAM KHALEEF BIN MOHD ROSDAN, AHSANA MASWA BINTI MOHD ROSDAN AND AMIRAH YASMIN BINTI MOHD ROSDAN.

MY BELOVED BROTHER AND SISTERS;
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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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MAI NURSHERIDA BINTI JALALUDDIN

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Chair: Professor Barkawi Bin Sahari, PhD. Ir.
Faculty: Engineering

Child crash dummies are commonly used for safety performance evaluations in vehicle crash tests. To analyze detail injuries in various body parts of a child, material modellling are useful, and provide information that cannot be obtained by crash dummies. To date, finite element (FE) modelling was gradually used to investigate child head dynamic response under drop test impact conditions. However, due to ethical reasons, none of developed one-year-old (1YO) head FE model was found to be quantitatively validated against child cadaver test at similar age group.

In the present research, a biofidelic FE model of 1YO head with fontanel, neck, and chest were developed to investigate child head dynamic response under drop impact conditions, neck pendulum analysis and frontal thorax impact analysis. The model was developed by using both deformable and rigid body materials, which consists of about 108,331 elements, and a morphing method within LS-Prepost software was used to morph the geometry. In order to determine the biofidelity of the skin and muscle of 1YO FE model with viscoelastic materials, the material properties need to be modelled accurately. There are three different cases of material modelling considered in this study. It is based on their level of difficulty and accuracy in the analysis to ensure that the desired accuracy level in the stress singularity analysis is attained. Case 1: The viscoelastic shear modulus is modelled as the standard linear solid model and Poisson's ratio is constant. Case 2: Poisson's ratio and Viscoelastic shear modulus are modelled as the standard linear solid model. Case 3: Both the Poisson's ratio and Viscoelastic shear modulus are modelled as the Wiechert Model. Using recently published material property data, the child skull, skin and scalp of the 1YO FE model was developed to study the response in head drop tests, neck pendulum tests and frontal thorax tests. The test procedures followed are in accordance to the specifications from National Highway Traffic Safety Administration (NHTSA) Appendix E Part 572 Subpart 152 (for head, neck and thorax analysis) and ECE-R44 (for thorax analysis). The characteristics of the 1YO child FE model proved to be close to the Anthropometric Test Device (ATD) and child threshold corridor. For the

head impact, a good correlation in terms of accelerations (g) between child cadaver experiment and simulation were obtained. For neck pendulum test and frontal thorax analysis, comparison of results indicated that the FE model showed fairly good biofidelic behaviour in both dynamic responses. The viscoelastic properties for Case-3 are determined using the best fit curve technique. From the results, it shows that the experimental curve of the viscoelastic shear modulus of human skin and muscle and the fitting curve were in accordance to the model described in Case-3. Even though this 1YO FE model has several limitations in areas such as the anatomical shapes of a child, this model can be useful tool to examine the behaviour of child impacts, which may be difficult to predict by using existing ATD dummy with its stiff material properties.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PEMBANGUNAN MODEL SEMU SATU TAHUN ASIA UNTUK MERAMALKAN KECEDERAAN DALAM KEMALANGAN AUTOMOTIF MENGGUNAKAN UNSUR TERHINGGA

Oleh

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Patung kemalangan kanak-kanak biasanya digunakan untuk penilaian prestasi keselamatan dalam ujian kemalangan kenderaan. Menganalisis kecederaan terperinci dalam bahagian-bahagian badan pelbagai kanak-kanak, bahan modellling berguna, dan memberikan maklumat yang tidak boleh diperolehi dengan patung kemalangan. Setakat ini, unsur terhingga (FE) pemodelan secara beransur-ansur digunakan untuk mengkaji tindak balas kepala kanak-kanak dinamik di bawah keadaan kesan ujian penurunan. Walau bagaimanapun, atas sebab-sebab etika, tiada dibangunkan berusia satu tahun (1YO) kepala model FE telah didapati secara kuantitatif disahkan terhadap ujian mayat kanak-kanak di peringkat umur yang sama. Dalam kajian ini, model biofidelic FE kepala 1YO dengan ubun, leher, dan dada telah dibangunkan untuk menyiasat tindak balas kepala kanak-kanak dinamik di bawah keadaan kesan drop, analisis bandul leher dan frontal analisis impak toraks. Model ini telah dibangunkan dengan menggunakan kedua-dua bahan ubah bentuk dan tegar badan, yang terdiri daripada kira-kira 108.331 elemen, dan kaedah morphing dalam perisian LS-Prepost digunakan untuk morph geometri. Dalam usaha untuk menentukan biofidelity pada kulit dan otot model 1YO FE dengan bahan-bahan viscoelastic, sifat-sifat bahan perlu dimodelkan dengan tepat.

Terdapat tiga kes yang berbeza pemodelan bahan dipertimbangkan dalam kajian ini. Ia adalah berdasarkan kepada tahap kesukaran dan ketepatan dalam analisis untuk memastikan tahap ketepatan yang dikehendaki dalam analisis tekanan ketunggalan dicapai. Kes 1: Modulus ricih viscoelastic dimodelkan sebagai model pepejal linear standard dan nisbah Poisson adalah tetap. Kes 2: Nisbah Poisson dan viskoelastik modulus ricih dimodelkan sebagai model pepejal linear standard. Kes 3: Kedua-dua nisbah Poisson dan viskoelastik modulus ricih dimodelkan sebagai Model Wiechert. Dengan menggunakan data yang diterbitkan baru-baru ini sifat bahan, tengkorak kanak-kanak, kulit dan kulit kepala model 1YO FE telah dibangunkan untuk mengkaji tindak balas dalam ujian penurunan kepala, ujian bandul leher dan ujian toraks hadapan.

Prosedur ujian diikuti adalah selaras dengan spesifikasi dari Negara Lebuhraya Keselamatan Trafik Pentadbiran (NHTSA) Lampiran E Bahagian 572 Sub 152 (untuk kepala, leher dan analisis toraks) dan ECE-R44 (untuk analisis toraks). Ciri-ciri model FE 1YO kanak-kanak terbukti berhampiran dengan Ujian Peranti antropometri (ATD) dan ambang anak koridor. Untuk kesan kepala, hubungan yang baik dari segi pecutan (g) antara eksperimen mayat kanak-kanak dan simulasi telah diperolehi. Untuk ujian bandul leher dan analisis toraks frontal, perbandingan keputusan menunjukkan bahawa model FE menunjukkan tingkah laku biofidelic yang agak baik dalam kedua-dua tindak balas dinamik. Sifat-sifat viscoelastic untuk kes-3 ditentukan dengan menggunakan teknik keluk patut terbaik. Daripada keputusan, ia menunjukkan bahawa lengkung eksperimen modulus ricih viscoelastic kulit manusia dan otot dan keluk pemasangan adalah mengikut model yang diterangkan dalam kes-3. Walaupun model 1YO FE ini mempunyai beberapa batasan dalam bidang-bidang seperti bentuk anatomi kanak-kanak, model ini boleh menjadi alat yang berguna untuk mengkaji tingkah laku kesan kanak-kanak, yang mungkin sukar untuk meramalkan dengan menggunakan dummy ATD yang sedia ada.

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I certify that a Thesis Examination Committee has met on (date of viva voce) to conduct the final examination of (student's name) on his (her) thesis entitled ("Title of Thesis") in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the (insert the name of relevant degree).

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

a	Acceleration
a(t)	Resultant acceleration
A	Cross sectional area
AFC	Anterior Fontanel Closure
ATD	Anthropometric Test Devices
CG	Center of Gravity
CSI	Chest Severity Index
E	Young Modulus
ECE	Economic Commission for Europe
EEVC	European Enhanced Vehicle-Safety Commitee
ETA	Engineering Technology Associates
F	Force
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
1YO	One-year-old
6MO	Six-month-old
g	Gravitational acceleration
GSI	Gadd Severity Index
Δ	Displacement
HIC	Head Injury Criterion
HIC (d)	Performance Criterion
K	Bulk Modulus
LSTC	Livermore Software Technology Corporation
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
NIC	Neck Injury Criteria
P	Force
PMHS	Post Mortem Human Specimen
RH	Reversible Hood
TBI	Traumatic Brain Injury
WHO	World Health Organization
WSTC	Wayne State Tolerance Curve
SEA	Specific Energy Absorption
SMC	Sheet Molding Compounds
σ	Stress
t	Time
T	Total pulse duration
U	Strain Energy
τ	Shear stress
γ	Shear strain
M	Torque/ Mass
θ	Angle
G	Elastic shear modulus
G□	Dynamic Modulus
G'	Storage Modulus
ν	Poisson ratio

CHAPTER 1

INTRODUCTION

1.1 Background

In early design stage, analysis is performed to the crashworthiness of vehicle body structure and passenger behavior. In the event of crash, the kinetic energy of the vehicle is converted into internal energy of the body structure. Since the vehicle body has limited capacity to absorb all the kinetic energy, the excess is transferred to the passenger. In the event there is physical contact between passenger and vehicle, injury may occur. To reduce injury to the passenger, energy dissipating components such as air bag restraint systems, seat belts and child seat restraint systems are designed and fitted to the vehicle.

Given its importance and effect on the population, the study of pediatric injury is greatly hindered by the lack of available pediatric post mortem human specimen (PMHS) data (Prange et al., 2004). Alternative test devices, such as child anthropometric test devices (ATDs) and finite element models (FEMs), are being used to enhance the study of child head injury (Melvin 1995; Irwin and Mertz 1997; Klinich et al. 2002). Unfortunately, the development of these tools and the understanding of their injury results suffer from the same limitation of a lack of available data (Melvin 1995; Irwin and Mertz 1997; Margulies and Thibault 2000; Klinich et al. 2002). To improve the understanding of child body biomechanics, a four-step research approach will be taken, namely; the development of original data, the testing of present injury theories, testing of the current models for accuracy, and the development of thresholds for pediatric injuries.

Although constant improvement in child occupant safety protection was done, the automotive crashes design is still not optimal. According to Arbogast et al. (Arbogast, 2014) the rate of injury for children is about 2.7 per 1000 crashes for frontal impact and 4.5 per 1000 crashes for side impact. This is already a relatively low rate. Still, through development of better child safety systems, particularly enhancement of the safety of the environment in cars, and improvement of the compatibility of child restraints with cars, the rate of injury for children can be further reduced.

Several adult Finite Element (FE) Model has been developed, but there are relatively few paediatric FE model due to scarcity of material property data for children. Therefore, there are not enough models representing one-year-old (1 YO) child. Child head injury, neck injury, and chest injury are costly problems, both in terms of morbidity and direct medical costs. In fact, it was the primary cause of death and disability for children under the age 18years. Despite its importance and effect on the population, the study of paediatric head injury, neck injury and chest injury are hindered by the lack of available paediatric PMHS data. As a substitute for PMHS testing, anthropometric test devices (ATDs) and FEM have been developed to model the 1 YO dummy. However, there is a scarcity of data for the design and validation of these models. In the present study, the development and validation of 1 YO FE dummy model and simulated results are compared with the child cadaver experimental data under variety of test conditions. There are three major child body parts that require separate test condition analysis. The parts are the head, neck and chest. Head analysis need to be validated under drop test condition, pendulum test is for neck injury analysis, and chest impact test is for chest injury analysis. In addition, the vehicle test was performed with the complete dummy for validation purposes. The test is car frontal impact analysis with one-year-old dummy sitting on the child car seat.

1.2 Problem Statement and Justification of Study

In the development of 1 YO Asian dummy model for the FE prediction of injury in automotive crash, every materials and parts of the child dummy must be validated by using previous research cadaver experimental data and the child safety needs to be determine. This is done by numerical simulation work using finite element on the vehicle with child dummy as occupant. Head Injury Criteria (HIC), Neck Injury Criteria (NIC) and Chest Severity Index (CSI) values are used to determine injury severity. Experimental work on life human is not performed due to ethical reasons. Hence, numerical modeling and simulation work are carried out using FE model of human (called dummy). Human body is biological living being. The body consists of living tissues such as bone, muscles, brain, heart and cartilage. Numerous adult Finite Element Model (FEM) has been developed, but there are relatively few paediatric FEM due to scarcity of material property data for children. Therefore, there are not enough models representing one-year-old child.

The property values depend on many parameters such as age, gender and mechanical stress experienced over time. Standard dummy model available in the market are applicable to European population. Therefore, child and adult dummies derived from Asian biomechanical data is required so that the injury prediction represent that for Asian population. Hence, a finite element dummy specific for Asian population is needed. This study will develop the one-year-old for Asian population for injury prediction of car.

1.3 Aim and Objective of study

In the present work, a biofidelic FE model of 1YO head with fontanel, neck, and chest were developed to investigate child head dynamic response under drop impact conditions (for head injury analysis), neck pendulum analysis (for neck injury analysis) and frontal thorax impact analysis (for chest injury analysis). The model was developed by using both deformable and rigid body materials, and a morphing method within LS-Prepost software was used to morph the geometry. In order to determine the biofidelity of the skin and muscle of 1YO FE model with viscoelastic materials, the material properties need to be modelled accurately. This child dummy will be used for passenger injury prediction in an automotive crash event. The analyses are for the frontal impact simulation and determining the injury criteria, namely HIC and CSI. The 1 YO child dummy development is established using finite element analysis program LS-DYNA to obtain a vehicle which is safe for 1 YO Asian occupant.

The objectives of this study are:

1. To formulate the material behavior model and determine the property values for the skin, bone and muscle material for 1 year old.

2. To build a calibrated model of a 1 year old Asian finite element dummy model for injury prediction.

3. To predict the HIC and CSI values of the 1 year old dummy under crash impact using finite element analysis.

1.4 Thesis outline

The purpose of this research is to create a FE model of the 1 YO anthropomorphic testing device (ATD) as a tool for safety research for children and to formulate the material property model for the skin, bone and muscle for 1 year old. The six year old dummy from LSTC was morphed and a finite element mesh representing the 1 YO dummy was refined. The material properties for the skin, bone and muscle were determined through previous research data from published journal papers. Then the material properties were validated with simulation tests. This thesis consists of six chapters. The first chapter is the introduction for this study that consists of introduction, problem statement, objectives and thesis outline. Reviews of literatures relevant to the present study are presented in the second chapter. The third chapter describes the methodology used to create the FE model of the 1 YO dummy and the modifications that have been done to the 1 YO dummy model. This includes strategies used to serve as guide throughout the process and to assist in achieving the objectives. The fourth chapter contains the detailed descriptions of geometry and material modelling used in carrying out present study that contains the results and findings of the component level simulations, the complete whole dummy simulations, the comparison of the 1 YO FE model to experimental dummy model that obtained from published journals. In chapter four, the results obtained from the finite element analyses are presented. This chapter discusses in detail the results and discussion of injury analyses of 1 YO FE model dummy. Finally the last chapter discussed the conclusions and recommendations for the present study.

REFERENCES

Advisory Group for Aerospace Research and Development (AGARD) (1996). *Anthropomorphic Dummies for Crash and Escape System Testing.* AR-330, Neuilly-Sur-Seine, France.

Alexander and Miller (1979). Determining skin thickness with pulsed ultrasound. *J Invest Dermatol* 72:17 - 19, 1979.

Arbogast et. al., (2004). Injury risks for children in child restraint systems in side impact crashes. *Traffic Injury Prevention*, Volume 6, Number 4, Taylor and Francis Ltd, pp. 351-360(10).

Atabaki, (2007). Pediatric head injury, *Pediatrics in Review,* 28: 215-224.

Ballesteroset. al., (2003). Differential ranking of causes of fatal versus non-fatal injuries among US children, *J.L. Annest. Injury Prevention*.

Bathe, (1982). *Finite Element Procedures in Engineering Analysis*. Prentice-Hall, Englewood Cliffs, NJ.

Bathe K.J. (1996). *Finite Element Procedures*. Prentice-Hall, Englewood Cliffs, NJ, USA.

Baumer et. al., (2009). Age dependent mechanical properties of the infant porcine parietal bone and a correlation to the human. *J Biomech Eng* 2009;131:111006.

Beer and Johnston, (1981). *Mechanics of Materials*. New York: McGraw-Hill.

Bigot et. al., (1996). Evolution during growth of the mechanical properties of the cortical bone in equine cannon-bones. *Med Eng Phys 1996.*

Brian Smith, Lawrence Valvo, (2012). *Test Procedure 208-14 Occupation Crash Protection* TP-208-14, National Highway.

Brodt et. al., (1999). Growing C57Bl/6 mice increase whole bone mechanical properties by increasing geometric and material properties. *J Bone Miner Res* 1999;14:2159–66.

Brown IB. (1972). Scanning electron microscopy of human dermal fibrous tissue. *J Anat* 1972.

Catherine et. al., (1989). Age-Related Mechanical Properties of Human Skin: An In-Vivo Study, *Journal of Investigative Dermatology* 1989.

Coats and Margulies, (2003). Characterization of paediatric porcine skull properties during impact, in: *Proceedings of the IRCOBI Conference*, Lisbon, 2003.

Coats and Margulies, (2006). Material properties of human infant skull and suture at high rates, *J. Neuro trauma* 23 (8) (2006) 1222–1232.

CDC. (1990). Childhood injuries in the United States, *American Journal of Diseases of Children*.

Chen, (1985). Growth Charts Based on Longitudinal Study of Malaysian Children from Birth to six years. *Med J. Malaysia.*

Choi and Zheng, (2005). Estimation of Young's modulus and Poisson's ratio of soft tissue from indentation using two different-sized indentors: finite element analysis of the finite deformation effect. Med. *Biol. Eng. Comput*., 2005.

Chou et. al., (1993). MADYMO2D/3D vehicle structural/occupant simulation models. *American Society of Mechanical Engineers*, AMD, Volume 169, 207-222.

Christian Gehre, (2005). Development of the Numerical Model of the Newborn Child Dummy Q0, L*S-DYNA Anwender forum*, Bamberg 2005.

Coats and Margulies, (2003). Characterization of paediatric porcine skull properties during impact, in: *Proceedings of the IRCOBI Conference*, Lisbon.

Coats and Margulies, (2006). Material properties of human infant skull and suture at high rates, *J. Neurotrauma*, 23(8): 1222-1232.

Coats et. al., (2007). Parametric study of head impact in the Infant. *Proceedings of Stapp Car Crash Journal*, 51: 1-15.

Cook R.D.,et. al., (1989). *Concepts and applications of finite element analysis*. Third edition, John Wiley & Sons, New York, NY, USA.

Cooper A et. al., (1994). Mortality and Truncal Injury: The Pediatric Perspective. *J Pediatr Surg*. 1994;29:33–38. Full Text Bibliographic Links.

Cotta-Pereira G,et. al., (1976). Oxytalan, elaunin, and elastic fibers in the human skin. *J Invest Dermatol* 1976: 66: 143-148.

Courant R., (1943). Variational Methods for the Solution of Problems of Equilibrium and Vibrations. Bulletin of the American Mathematical Society, Vol. 49, pp. 1–23.

Daniel Baumgartner and Remy Willinger. (2005). Numerical Modelling of the Human Head Under Impact: New Injury Mechanism And Tolerance Limits.

D. Gilchrist (ed) *IUTAM Proceedings on Impact Biomechanics: From Fundamental Insights to Applications*, 195-20. 2005.

Daryl L. Logan, (2007). *A First Course in the Finite Element Method*, Fourth Edition, Thomson.

Davies et. al., (1975). Anterior fontanelle size in the neonate. *Arch Dis Child*., 50: 81-83.

Denton ATD, (2004). *History of Anthropomorphic Test Devices*. www.tno-automotive.cn/knowledge/MADYMO_UM/2004International/P1.pdf.

DOT (Department of Transportation), National Highway Traffic Safety Administration, (1972). *Occupant Crash Protection – Head Injury Criterion S6.2 of MVSS 571.208*, Docket 69-7,Notice 17. NHTSA, Washington, DC.

Derek S. Wheeler et. al.,(2014). *Pediatric Critical Care Medicine: Volume 2: Respiratory, Cardiovascular and Central Nervous Systems*. Springer Second Edition.

Dunn MG and Silver FH, (1983). Viscoelastic behavior of human connective tissues: relative contribution of viscous and elastic components. *Connect Tissue Res* 1983.

Dunn MG. and Silver FH, Swann DA. (1985). Mechanical analysis of hypertropic scar tissue: structural basis of apparent increased rigidity. *J Invest Dermatol* 1985: 84: 9-13.

Edward M et al., (2007). Current Status of the Full Width Deformable Barrier Test, Paper No. 88, 20th *ESV conference, Lyon, 2007*.s.

Eiband, (1959). Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature. *NASA Memo 5-19-59 E.*

Elaheh Ghassemieh, (2011). *Materials in Automotive Application, State of the Art and Prospects, New Trends and Developments in Automotive Industry*, Prof. Marcello Chiaberge (Ed.), ISBN: 978-953-307-999-8, InTech.

Eppinger et. al., (2000). Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems-II. National Highway Traffic Safety Administration.

Eric et. al., (1996). Young's Modulus Measurements of Soft Tissues with Application to Elasticity Imaging, *IEEE Transactions on Ultrasonics, Ferroeletrics, and Frequency*.

Euro NCAP., (2012). *ASSESSMENT PROTOCOL – OVERALL RATING* . Version 7.0

Faruque et. al., (1996). Linear visco-elastic material model for headform skin with applications to interior head impact protection. *American Society of Mechanical Engineers*. Applied Mechanics Division.

Frederick H.Silver et. al., (2001). Viscoelastic properties of human skin and processed dermis. *Skin Research and Technology* 2001: 7:18-23.

Freed et. al., (2010). Hypoelastic soft tissues. *Acta Mechanica.*
Fuchs et. al., (1989). Cervical Spine Fractures Sustained by Young Children in Forward-Facing Car Seats. *Pediatrics*, 84(2), pp. 348-354

Gadd, (1966). Use of a Weighted-Impulse Criterion for Estimation Injury Hazard, SAE Paper No. 660793, in: *10th Stapp Car Crash Conf., Society of Automotive Engineers*.

George R. Buchanan (1995). *Theory and Problems of Finite Element Analysis.* McGraw-Hill.

George Korbetis, (2011). Usage of fully detailed CAE models for concept design with the ANSA Morphing Tool, *8 th European LS-DYNA Users Conference*, Strasbourg.

Hailing Yu et. al., (2007). Three-dimensional finite element modelling of the torso of the anthropometric test device THOR. *Int. J. Of Vehicle Safety.*

Hallquist, (1998). *LS-DYNA Theoretical Manual*, Livermore Software Technology Corporation, Livermore, CA, USA, Chap. 21 25.

Hassan et. al., (2012). The Nonlinear Elastic and Viscoelastic Passive Properties of left venticular pappilary muscle. *Journal of the Mechanical Behaviour of Biomedical Materials*.

Hrapko et. al., (2006). The mechanical behaviour of brain tissue: large strain response and constitutive modeling, *Biorheology* 43 (2006), 623–636.

Herrmann and Peterson, (1968). *A Numerical procedure for Viscoelastic Stress Analysis*. In: Proceedings of the Seventh Meeting of ICRPG Mechanical Behavior Working Group.

Hodgson and,Thomas, (1975). Head impact response. *Vehicle Research Institute VRI Report*. VRI 7.2 SAE. 1975.

Hrennikoff, A. (1941). Solution of Problems in Elasticity by the Frame Work Method. *Journal of Applied Mechanics*, Vol. 8, No. 4, pp. 169–175, Dec. 1941.

Humanetics Innovative Solutions, 2011. Website:

http://www.dentonatd.com/dentonatd/anthropomorphic.html.

Huelke D., (1998). An Overview of Anatomical Considerations of Infants and Children in the Adult World of Automobile Safety Design. *Proceedings of the 42nd Annual AAAM Meeting*, Charlottesville, VA, October 1998.

Huelke et. al., (1992). Car Crashes and NonHead Impact Cervical Spine Injuries in Infants and Children. *Sot Auto Eng IntZ Cong*, Paper No. 920562, Detroit.

Huja SS et. al., (2008). Changes in mechanical properties of bone within the mandibular condyle with age. *J Morphol* 2008;269:138-43.

Indrekvam K. et. al., (1991). Age dependent mechanical properties of rat femur. Measured in vivo and in vitro. *Acta Orthop Scand* 1991;62:248–52.

Irwin and Mertz, (1997). Comparison of the EUROSID and SID Impact Responses to the Response Corridors of the International Standards Organisation".

Isaksson et. al., (2010). Rabbit cortical bone tissue increases its elastic stiffness but becomes less viscoelastic with age. *Bone* 2010;47:1030–8.

Jacob et. al., (2014). Development, Calibration, and Validation of a Head–Neck Complex of THOR Mod Kit Finite Element Model. *Traffic Injury Prevention*.

Jacob et. al., (2002), Energy Absorption in Polymer Composites for Automotive Crashworthiness, *Journal of Composite Materials.*

Johnson and Walton, (1983a). An experimental investigation of the energy dissipation of a number of car bumpers under quasi-static lateral loads. *International Journal of Impact Engineering,* 1(3), 301-308.

Johnson, (1990). *The elements of crashworthiness: scope and actuality*, Professional Engineering, London, Royaume-Uni.

Johnson and Walton, (1983b). Protection of car occupants in frontal impacts with heavy lorries: Frontal structures. *International Journal of Impact Engineering*.

Jonathan Pindrik et. al., (2014). Anterior Fontanelle Closure and Size in Full-Term Children Based on Head Computed Tomography. *Clinical Pediatrics*, Sage Publications.

Julian Vincent (1990), *Structural Biomaterials*, Princeton University Press; Revised edition.

Julian Happian-Smith, (2002). *An Introduction to Modern Vehicle Design*. Butterworth-Heinemann, 0750650443.

Jachowicz et al., (2007). Indentometric analysis of in vivo skin and comparison with artificial skin models, *Skin Research and Technology*.

Kasai et. al., (1996). Growth of the Cervical Spine With Special Reference To Its Lorclosis and Mobility, *Spine*, 21(18): 2067-2073.

Kate de Jager and Michiel van Ratingen, (2005). Assessing New Child Dummies And Criteria For Child Occupant Protection In Frontal Impact, *Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV)* Paper no. 05-0157.

Keller TS et. al., (1986). Geometric, elastic, and structural properties of maturing rat femora. *J Orthop Res* 1986;4:57–67.

Khor GL et. al., (2009). Nutritional Status of Children below Five Years in Malaysia:

Anthropometric Analyses from the Third National Health and Morbidity Survey III (NHMS, 2006) *Mal J Nutr.*

Kiesler and Ricer, (2003). The abnormal fontanel. *Am Fam Physician.*

Kim et. al., (2010). Determination of shear and bulk moduli of viscoelastic solids from the indirect tension creep test. *Journal of Engineering Mechanics.*

Kleinberger et. al., (1998). Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems. *National Highway Traffic Safety Administration*. http://www-nrd.nhtsa.dot.gov/pdf/nrd-11/airbags/criteria.pdf.

Klinich et. al., (2002). Estimating Infant Head Injury Criteria and Impact Response Using Crash Reconstruction and Finite Element Modeling. *Stapp Car Crash Journal* 46: 165-194.

Knothe and Wessels, (1999). *Finite Elemente: Eine Einführung für Ingenieure*. Springer Verlag, Berlin, Germany, Chap. 3.

Konder, (1963). Hyperbolic stress-strain response: cohesive soils. *Journal of the soil mechanics and foundations division*, ASCE, 89(1), 115-143.

Kraus et. al., (1990). Brain injuries among infants, children, adolescent, and young adults. *American Journal of Diseases of Children*, 144:684-691.

Langlois et. al., (2006). Traumatic Brain Injury in the United States: Emergency Department Visits, Hospitalizations, and Deaths, Centers for Disease Control and Prevention. N*ational Center for Injury Prevention and Control.*

Lasry et. al., (1991). Mathematical modelling of the Hybrid III dummy chest with chest foam. Proceedings-Society of Automotive Engineers Issue P-251, 1991, Pages 65-72, P*roceedings of the 35th Stapp Car Crash Conference.*

Lavker et. al., (1987). Age skin: a study by light, transission electron, and scanning electron micrsopy. *J Invest Dermatol* 1987: 88: 44s-51s.

Lewis and Ward, (1991). *The Finite Element Method: Principles and Applications*, Addison Wesley Publishing Company, Boston, MA, USA.

LEE, (1962). *Viscoelasticity*. In Handbook of Engineering Mechanics (edited by W.FLVGGE), Chapter 53. McGraw-Hill, New York.

Li et. al., (2011). Development, validation, and application of a parametric pediatric head finite element model for impact simulations. *Annals of Biomedical Engineering*, 39: 2984-2997.

Li et. al., (2013). Erratum to: Development, validation, and application of aparametric pediatric head finite element model for impact simulations. *Annals of Biomedical Engineering.*

Li et. al., (2013). Development/global validation of a 6-month-old pediatric head finite element model and application in investigation of drop-induced infant head injury, *Computer Methods and Programs in Biomedicine II* 2: 309-319.

Lissner, (1960). Experimental Studies on the Relation between Acceleration and Intracranial Pressure Changes in Man. Surgery, *Gynecology and Obstetrics.*

Loyd (2011). *Studies of the Human Head from Neonate to Adult: An Inertial, Geometrical and Structural Analysis with Comparisons to the ATD Head Child Anthropometry for Restraint System Design*. Thesis, Graduate School of Duke University, 606 pages, 2011.

Maltese and Eppinger, (2002). Development of improved injury criteria for the assessment of child restraint systems, *NHTSA Docket,* 2002- 11707-18.

Marcia Vita National, (2002). *Institute of Neurological Disorders and Stroke National Institutes of Health Bethesda, Maryland* 20892-2540, NIH Publication No. 02-158 September, 3-4.

Margulies and Thibault, (2000). Infant skull and suture properties: Measurements and implications for mechanisms of pediatric brain injury. *Journal of Biomechanical Engineering*, 122, 364–371.

Marion Geerligs et. al., (2011). Linear shear response of the upper skin layers. *Biorheology* 48

Marius Ispas, (2013). 3D Modeling for Car Body Design, *Journal of Industrial Design and Engineering Graphics*, 2013.

McClafferty et. al.,, (2007). Event Data Recorders in The Analysis of Frontal Impacts, 51st *Annual Proceedings Association for The Advancement of Automotive Medicine.*

McHenry, (1943). A Lattice Analogy for the Solution of Plane Stress Problems. *Journal of Institution of Civil Engineers*, Vol. 21, pp. 59–82, Dec. 1943.

Melvin, (1995) Injury Assessment Reference Values for the CRABI 6-Month Infant Dummy in a Rear-Facing Infant Restraint with Air Bag Deployment. *SAE International Congress and Exposition*, SAE Paper No. 950872.

Mertz, et. al, (1997). Injury Risk Curves for Children and Adults in Frontal and Rear Collisions. SAE Paper No. 973318. *Society of Automotive Engineers*. 13 -30.

Mertz,.(1985). Anthropomorphic models. The biomechanics of trauma. Appelton-Century-Crofts, Norwalk, CT, USA

Mertz, (1993). *Anthropomorphic Test Devices. Accidental injury: biomechanics and prevention*. Springer, New York, NY, USA

Michael, (2001). Cervical spine anatomy and function for the anesthesiologist, *Can J. Anesth.*

Mizuno et. al., (2007). Effectiveness of seatbelt for rear seat occupants in frontal crashes. *Proceedings of the 20th Conference on the Enhanced Safety of Vehicles (ESV)*, Lyon France, Paper No. 07-0224, June 2007.

Moore et. al., (1959). Child Injuries in Automobile Accidents. Presented at I & h Zntl *Conf Pediatrics, Montreal Canada*.

Morello et. al., (2011). *The Automotive Body: Volume I: Components Design*, Springer.

Mukherjee et. al., (2007). Finite Element crash simulations of the human body; Passive and active muscle modelling. *S adhan* Vol. 32, Part 4, August 2007, pp. 409-426

Nafei et. al., (2000). Properties of growing trabecular bovine bone. Part I: mechanical and physical properties. *J Joint Surg Br* 2000;82;910–20

Nahum et al., (1971). The biomechanical basis for chest impact protection. I. Force-deflection characteristics of the thorax. *J Trauma*. 1971;11:874–882.

NHTSA, (2001). *Dummy Performance Calibration in Support of Vehicle Safety Compliance Testing for Occupant Crash Protection Report Documentation.*

Norlen Mohamed et. al. (2011). *An Overview of Road Traffic Injuries Among Children in Malaysia and Its Implication on Road Traffic Injury Prevention Strategy*. MIROS Research Report, MRR03/2011.

Nursherida et. al.,(2012a). Performance of hood system and head injury criteria subjected to frontal impacts. *Applied Mechanics and Materials* 165.

Nursherida, et. al., (2012b). Determination of leg injury criteria subjected to frontal impacts. *Applied Mechanics and Materials* pp 265-269.

Ohman et. al, (2008). The effects of embalming using a 4% formalin solution on the compressive mechanical properties of human cortical bone. Clin Biomech.

Ohman et. al., (2011). Compressive behaviour of child and adult cortical bone. *Bone 2011*; 49: 769–776 (2012)

Ouyang Jun et. al., (2006). Thoracic Impact Testing of Pediatric Cadaveric Subjects, *The Journal of Trauma: Injury, Infection, and Critical Care.*

Oxland et. al., (1988). The role of elastin in the mechanical properties of skin. *J Biomech 1988*: 21: 213-218.

Paine and Brown, (2001). Crash and sled tests using child dummies. *Proceedings of the Impact Biomechanics Australia Conference* 2001.

Park et. al, (2011). Analysis of Child Dummy Responses and CRS Performance in Frontal NCAP Tests. N*ational Crash Analysis Center (NCAC)*, The George Washington University USA Paper Number 11-0142, 2011.

Pedrosoet. al., (2008). Evolution of anterior fontanel size in normal infants in the first year of life. *J Child Neurol*., 23: 1419-1423.

Prange et. al., (2004). Mechanical Properties and Anthropometry of the Human Infant Head, *Stapp Car Crash Journal* Vol. 48: 279–299.

Press et. al., (2007). *Numerical Recipes*. Third edition, Cambridge University Press, New York, USA, Chap. 10.

Puzrin, (2012). *Constitutive Modelling in Geomechanics*, DOI 10.1007/978-3-642-27395-7-13, Springer-Verlag Berlin Heidelberg.

Ramberg and Osgood, (1943). Description of Stress-Strain Curves by Three Parameters, Tec. Note 902, *National Advisory Comm. Aeronaut*.

Ramshaw JA. (1986). Distribution of type III Collagen in bovine skin of various ages. *Connect Tissue Res* 1986: 14" 307-314.

Rath et. al., (2000). Factors regulating bone maturity and strength in poultry. *Poult Sci* 2000;79:1024–32.

Roth et. al., (2007a). Finite element analysis of impact and shaking inflicted to a child. *International Journal of Legal Medicine*, 121(3):223-228.

Roth et. al.,(2007b). Limitation of scaling methods in child head finite element modeling. *International Journal of Vehicle Safety*, 2(4): 404-421.

Roth et. al., (2008). Biofidelic child head FE model to simulate real world trauma. *Computer Methods and Programs in Biomedicine*, 90: 262-274.

Roth et. al., (2010). Finite element modeling of paediatric head impact: global validation against experimental data. *Computer Methods and Programs in Biomedicine*, 99: 25-33.

Saunders, (2006). NHTSA's research program for adult rear occupants in frontal crashes. *SAE Industry/Government Meeting*, Washington DC, May 2006.

Shams et. al., (2003). Design of temperature insensitive ribs for crash test dummies. SAE *Technical Papers 2003 SAE World Congress*; Detroit, MI; United States; 6 March 2003.

Silver, (1987), Biological materials; structure, mechanical properties, and modeling of soft tissues. *New York N. Y. U*. Press, 1987: 75-79, 164-195.

Silver et. al., (1992). Analysis of mammalian connective tissue: relationship between hierarchical structures and mechanical properties. *J Long-term Effect Med Implants* 1992: 2: 165-198.

Silver et. al., (2000a). Transition from vaiscous to elastic-dependency of mechanical properties of self-assembled collagen fibers. *J Appl Polymer Sci* (in press)

Silver et. al., (2000b). Role of storage on changes in the mechanical properties of tendon and self-assembled collagen fibers. *Connect Tissue Res* 2000: 41: 155-164

Silver et. al., (2000c). The role of mineral in the viscoelasticity of turkey tendons. *Biomacromolecules* 2000: 1: 180-185

Silver et. al., (2003). Collagen self-assembly and the development of tendon mechanical properties. *J Biomech* (in press)

Smith, (1982). Structure of the dermal matrix during development and in the adult. *J Invest Dermatol* 1982: 79: 93s-104s.

Srirangam Kumaresan et. al., (1997). Paediatric Neck Modelling using Finite Element Analysis. *International Journal of Crashworthiness*, 2:4, 367-376, DOI: 10.1533/cras.1997.0055.

Sturtz G. (1980). Biomechanical Data of Children. SAE Paper Number 801313. Warrendale, PA: *Society of Automotive Engineers*, 1980.

Sujit Chalipat et. al. (2008). *Use of Morphing Tool to Build Parametric Finite Element Vehicle Model*, Altair India Driving Innovation with Enterprise Simulation Event.

Thomas et. al., (2007). *Pediatric critical care medicine: basic science and clinical evidence*. Berlin: Springer. p. 666. ISBN 1-84628-463-5.

Thomas W. Birch. (2000). *Automotive Chassis System*. Delmar Thomson Learning.

Timoshenko and Goodier, (1970). *Theory of Elasticity*. McGraw-Hill: New York.

TNO, (2003). *MADYMO Database manual version 6.1*, TNO Automotive, Delft.

Torzilli et. al., (1982). The material properties of immature bone. *J Biomech Eng* 1982.

Tschoegl et al. (2002). Poisson's Ratio in Linear Viscoelasticity – A Critical Review. *Mechanics of Time-Dependent Materials* 2002

Tylko and Dalmotas, (2005). *Protection of rear seat occupants in frontal crashes*. Proceedings of the 19th Conference on the Enhanced Safety of Vehicles (ESV), Washington DC, Paper No. 05-0258, June 2005.

Umashankar Mahadevaiah et. al., (2013). Documentation of LSTC Hybrid III 6-year-old FEM.

Untaroiu and Lu, (2011). *A simulation-based calibration and sensitivity analysis of a finite element model of THOR head–neck complex*. Paper presented at: SAE 2011 World Congress & Exhibition, 2011; Detroit, MI.

Van Dam et. al., (2006). Determination of linear viscoelastic behavior of abdominal aortic aneurys thrombus, *Biorheology* 43 (2006), 695–707.

Van Lopik and M Acar, (2007). Development of a multi-body computational model of human head and neck. *Proceedings of the Institution of Mechanical Engineers*, Part K: Journal of Multi-body Dynamics, June 1, 2007 vol 221 no 2 175-197.

Van Turnhout et. al., (2005). Passive transverse mechanical properties as a function of temperature of rat skeletal muscle in vitro, *Biorheology* 42 (2005), 193–207.

Versace, (1971). *A Review of the Severity Index*, in: 15th Stapp Car Crash Conference, SAE Technical paper No. 710881, 771-796.

Viano DC et al., (1989). Bio-mechanics of the human chest, abdomen, and pelvis in lateral impact. *Accid Anal Prev.* 1989;21:553–574.

Viano D. et. al., (1997). Serious brain injury from traffic related causes: priorities for primary intervention. *Accid. Anal. Prev.*, 29: 811-816.

Vitallaro-Zuccarello et. al., (1994). Stereological analysis of collagen and elastic fibers in the normal human dermis: Variability with age, sex and body region. *Anat Rec*:238: 153-162.

Weber, (1984). Experimental studies of skull fractures in infants. Zeitschrift fur, Rechtsmedizin. *Journal of Legal Medicine*, 92: 87-94.

Weber et. al., (1985a). *Child Anthropometry for Restraint System Design*, The University of Michigan, 1985, 34 pages.

Weber, (1985b). Biomechanical fragility of the infant skull. Zeitschrift fur Rechtsmedizin. *Journal of Legal Medicine*, 94: 93-101.

Wiecel et. al., (1985). *Enhancement of the Hybrid III dummy thorax*. Proceedings-Society of Automotive Engineers, Pages 147-158 29th Stapp Car Crash Conference Proceedings.

Willinger and Taleb, (1995). Modal temporal analysis of head mathematical models. J*ournal of Neurotrauma* 12 (4) 743–754.

WHO, (2008), World report on child injury prevention, Accessed on 2 February 2011, from www.unicef.org/eapro/World_ report.pdf.

Woods and Johnson. (2010). Absence of the anterior fontanelle due to a fontanellar bone. *J of Craniofac Surg.*, 21: 448-449.

Yijun Liu, (2013). *Introduction to Finite Element Method*, CAE Research Laboratory Document, University of Cincinnati USA, 2013

Yi et. al., (2011). Finite Element Modelling of a Hybrid III dummy and material identification for validation. Proceedings of the Institution of Mechanical Engineers, Part D. J*ournal of Automobile Engineering* Volume 225, Pages 54-73.

Yoganandan et al. (1995). Thoracic deformation and velocity analysis in frontal impact. *J Biomech Eng*. 1995;117:48–52. Full Text Bibliographic Links

Zhang et. al., (2001a). Comparison of brain responses between frontal and lateral impacts by finite element modeling. *Journal of Neurotrauma*.

Zhang, et. al., (2001b). Recent advances in brain injury research: a new human head model development and validation. *Stapp Car Crash Journal*.

Zhang et. al., (2011). Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 2—Comparison with Experimental Data from Literature, *Science and Technology for the Built Environment Journal*

Zhou, (2001). *Applications of cellular materials and structure in vehicle crashworthiness and occupant protection*, in Engineering Plasticity and Impact Mechanics (ed. L.C. Zhang), World Scientific, Singapore."