



UNIVERSITI PUTRA MALAYSIA

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

MAI NURSHERIDA BINTI JALALUDDIN

FK 2017 44



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AUTOMOTIVE CRASH**

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**

May 2017

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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 NAQUIDDIEN BIN MOHD
ROSDAN, ASLAM KHALEEF BIN MOHD ROSDAN, AHSANA MASWA BINTI MOHD
ROSDAN AND AMIRAH YASMIN BINTI MOHD ROSDAN.*

*MY BELOVED BROTHER AND SISTERS;
MAI JUZILIN BINTI HAJI JALALUDDIN, MAI JASMINA BINTI HAJI JALALUDDIN,
MAI SHAHZIMA
BINTI HAJI JALALUDDIN, MIOR NUR IZAM BIN HAJI JALALUDDIN AND
ALLAHYARHAMMAH
LEFTENAN MAI ELNY SEFRINA BINTI HAJI JALALUDDIN*

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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

By

MAI NURSHERIDA BINTI JALALUDDIN

May 2017

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 modelling 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
MENGUNAKAN UNSUR TERHINGGA**

Oleh

MAI NURSHERIDA BINTI JALALUDDIN

Mei 2017

Pengerusi: Profesor Barkawi Bin Sahari, PhD. Ir.

Fakulti: Kejuruteraan

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 modelling 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.

ACKNOWLEDGEMENTS

First and foremost, praises to Allah, the most Gracious and most Merciful, for giving me the opportunity to complete this research. I would like to express a sincere gratitude to my supervisor, Professor Ir. Dr. Barkawi Bin Sahari, for his guidance, support and encouragement during my doctoral study. His effort, advice and insight throughout this research enable me to develop an understanding of the research needed. I also would like acknowledge my supervisory committee, Assoc. Prof. Dr Nuraini Binti Abdul Aziz and Professor Manohar A/L Arumugam, for their outstanding advices and assistance during this period of study.

On a personal note, special gratitude to my beloved parent, Allahyarham Jalaluddin Bin Udin, Allahyarhamah Sharipah Sapiyah Bt Syed Hassan Al-Jamalulail, my spouse Mohd Rosdan Bin Sulaiman, my children, Aishah Umairah, Akid Naquiuddin, Aslam Khaleef, Ahsana Maswa and Amirah Yasmin for their love, support and blessing during my hardness time in completing this research.

I am indebted to very helpful and cooperative Green Technology lab postgraduate friends of Faculty of Mechanical Engineering, for their support, help and suggestions throughout my work especially Syazwan Abdul Samad, Siti Marhainis, Cik Suhana and to all my friends in Green Technology lab.

Finally, I would like to thank to Ministry of Higher Education Malaysia (MoHE) for MyBrain15 scholarship and Fundamental Research Grant Scheme with Reference Number: FRGS/2/2013/TK01/UPM/01/1, vot 55243555, Ministry of Education (MOE), Malaysia, for the financial support which enable me to complete my study.

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Members of the Thesis Examination Committee were as follows:

Mohd Sapuan bin Salit @ Sinon, PhD

Title (e.g., Professor/Associate Professor/Ir; omit if irrelevant)

Name of Faculty

Universiti Putra Malaysia

(Chairman)

Name of Examiner 1, PhD

Title (e.g., Professor/Associate Professor/Ir; omit if irrelevant)

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Title (e.g., Professor/Associate Professor/Ir; omit if irrelevant)

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Name of External Examiner, PhD

Title (e.g., Professor/Associate Professor/Ir; omit if irrelevant)

Name of Department and/or Faculty

Name of Organisation (University/Institute)

Country

(External Examiner)

(Insert name of current Deputy Dean)

(E.g. XXXXX XXXX, PhD)

Professor and Deputy Dean

School of Graduate Studies

Universiti Putra Malaysia

Date:

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Barkawi Bin Sahari, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Manohar a/l Arumugam

Professor
Faculty of Medicine and Health Sciences
Universiti Putra Malaysia
(Member)

Nuraini Binti Abdul Aziz, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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Signature: _____

Name of Chairman of
Supervisory Committee:

Prof. Ir. Dr. Barkawi Bin Sahari

Signature: _____

Name of Member of
Supervisory Committee:

Prof. Dr. Manohar a/l Arumugam

Signature: _____

Name of Member of
Supervisory Committee:

Assoc. Prof. Dr. Nuraini Binti Abdul Aziz

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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 Committee
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.

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