UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF THREE-YEAR OLD NIGERIAN NUMERICAL CHILD DUMMY MODEL FOR VEHICLE SAFETY ASSESSMENT

IBRAHIM ABDULLAHI RAFUKKA

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By

IBRAHIM ABDULLAHI RAFUKKA

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

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

DEVELOPMENT OF THREE-YEAR OLD NIGERIAN NUMERICAL CHILD DUMMY MODEL FOR VEHICLE SAFETY ASSESSMENT

By

IBRAHIM ABDULLAHI RAFUKKA

April 2017

Chairman : Professor Barkawi Bin Sahari, PhD
Faculty : Engineering

Child injuries in vehicular crashes especially on the head, is considered a major public health problem worldwide. Biofidelic child dummy is a key to designing safer vehicle to child occupants. Current crash dummies used for the evaluation of vehicle safety performance were developed based on 50^{th} percentiles of some specific populations of the world. Biomechanical response of child occupant on crash depends on the size and weight; Nigerian children need crash dummy model with biofidelic head representing their own anthropometry for crash test of vehicle used by this vulnerable population. The aim of this work is to develop three year old Nigerian child dummy model that can predict injuries from various head locations for application in vehicle crash test.

In the present work, anthropometric comparison was conducted where significant difference was found between the three year old Nigerian child (3YO NC) and current three year old Hybrid III (3YO HIII) and Q3s dummies with a maximum difference of more than 25% in body dimensions. To develop dummy for 3YO NC anthropometry, morphing technique in LS-DYNA software was used. It was first verified by developing a 3YO HIII dummy finite element (FE) model using six year old Hybrid III (6YO HIII) FE dummy model as a reference, and its biomechanical responses were compared with experimental and simulation results using physical 3YO HIII dummy from which it was found to be consistent both qualitatively and quantitatively. Detailed development of 3YO NC dummy model using the same scaling procedures was then accomplished. In this case, the body segments were morphed and material properties were modelled. The dummy head model was validated against the experimental data inferred from a nine year old child cadaver head recently published in literature for five impact locations namely; frontal, right and left parietals, vertex and occipital. The difference between child head FE model and scaled cadaver data is approximately 3% to 24%. The neck and thorax responses were also validated against three year old certification corridors, cadaver data and by comparison with other three year old child dummy models response available in the

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literature. The 3YO NC dummy response was found to be closer to certification corridors than the existing 3YO HIII dummy in some parameters. Other body parts were morphed and their material properties were modelled such that the weight fit that of 3YO NC. Comparison between morphed 3YO NC and morphed 3YO HIII in chest acceleration and upper neck moment and forces shows difference of approximately 6.5% to 41% between the two dummies.

Finite element model of child restraint seat (CRS) was also developed and validated to accommodate the child model in crash simulations. Crash analysis was conducted in LS-DYNA software with newly developed Nigerian child dummy in CRS using the Ford Taurus 1992 FE model in order to evaluate its crashworthiness capability with respect to three year old child occupants. The three year old child injury parameters: Head Injury Criteria (HIC_{15}, HIC_{36}) and neck moment (NM) were found to be 47%, 49% and 85% respectively above the NHTSA threshold while upper neck force and chest deflection were found to be within an acceptable range.

The technique employed in this study can be applied to develop dummy FE model of various sizes from existing crash dummy models. Biofidelic head model can be used to estimate injuries from vehicle crash due to contact of head with vehicle interior and height fall accidents for various head locations.

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

PEMBANGUNAN MODEL DAMI BERANGKA KANAK–KANAK TIGA TAHUN NIGERIA UNTUK PENILAIAN KESELAMATAN KENDERAAN

Oleh

IBRAHIM ABDULLAHI RAFUKKA

April 2017

Pengerusi : Profesor Barkawi Bin Sahari, PhD
Fakulti : Kejuruteraan

Kecederaan kanak-kanak dalam nahas kenderaan terutama bahagian kepala, merupakan masalah kesihatan awam utama dunia.Dami kanak-kanak biofidelik merupakan kunci bagi reka bentuk kenderaan yang lebih selamat bagi penumpang kanak-kanak. Dami nahas kini yang telah digunakan untuk penilaian bagi prestasi keselamatan kenderaan telah dibangunkan berdasarkan 50^{th} persentil bagi beberapa populasi tertentu dunia. Respon biomekanikal bagi penumpang kanak-kanak ke atas nahas bergantung kepada saiz dan berat; kanak-kanak Nigeria memerlukan model dami nahas dengan kepala biofidelik yang mewakili antropometri mereka sendiri bagi ujian nahas kenderaan yang digunakan oleh populasi yang lemah ini. Tujuan kajian ini adalah untuk membangunkan model dami kanak-kanak tiga tahun Nigeria yang dapat meramalkan kecederaan dari pelbagai lokasi kepala bagi diaplikasikan dalam ujian nahas kenderaan.

Dalam kajian ini, perbandingan antropometrik telah dijalankan dan didapati bahawa terdapat perbezaan yang signifikan antara kanak-kanak Nigeria berusia tiga tahun (3YO NC) dengan Hibrid III (3YO HIII) tiga tahun kini dan dami Q3 dengan perbezaan maksimum lebih daripada 25% dalam dimensi tubuh. Untuk membangunkan dami bagi antropometri 3YO NC, teknik morfing dalam perisian LS-DYNA digunakan. Perisian ini pertama kalinya telah ditentusahkan, dengan membangunkan model unsur terhingga (FE) dami 3YO HIII menggunakan model dami FE Hibrid III enam tahun (6YO HIII) sebagai rujukan, dan respon biomekanikal telah dibandingkan dengan dapatan uji kaji dan simulasi menggunakan dami 3YO HIII fizikal yang didapati adalah konsisten bagi kedua-dua ukuran, kuantitatif dan kualitatif. Perkembangan yang mendalam mengenai model dami 3YO NC menggunakan teknik penskalaan yang sama kemudiannya telah dilaksanakan. Dalam kes ini, segmen tubuh telah dimorfkan dan ciri bahan telah dimodelkan. Model kepala dami telah disahkan terhadap data uji kaji yang disimpulkan daripada kepala kadaver kanak-kanak sembilan tahun yang baru-baru ini diterbitkan dalam sorotan kajian untuk lima lokasi impak, iaitu; bahagian hadapan, kanan dan kiri parietals, verteks

dan oksipital. Perbezaan antara model FE kepala kanak-kanak dan data kadaver terskala ialah lebih kurang 3% hingga 24%. Respon leher dan toraks juga telah disahkan terhadap koridor pensijilan tiga tahun, data kadaver dan melalui perbandingan dengan tindak balas model dami kanak-kanak tiga tahun lain yang terdapat dalam sorotan kajian. Respon dami 3YO NC didapati hampir dengan koridor pensijilan daripada dami 3YO HIII yang sedia ada dalam beberapa parameter. Bahagian tubuh lain telah dimorfkan dan ciri bahan dimodelkan supaya berat diselarasuaikan dengan 3YO NC. Perbandingan antara 3YO NC yang dimorfkan dan 3YO HIII yang dimorfkan dalam pecutan dada dan momen leher atas dan tenaga menunjukkan perbezaan lebih kurang 6.5% hingga 41% antara kedua-dua dami tersebut.

Model unsur terhingga kerusi penahan kanak-kanak (CRS) juga telah dihasilkan dan disahkan bagi menyesuaikan model kanak-kanak dalam simulasi nahas. Analisis nahas telah dijalankan menggunakan perisian LS-DYNA dengan dami kanak-kanak Nigeria yang baru dibangunkan dalam CRS menggunakan model FE Ford Taurus 1992 bagi menilai kebolehan perlindungan laganya dengan merujuk kepada penumpang kanak-kanak tiga tahun. Parameter kecederaan kanak-kanak tiga tahun: Kriteria Kecederaan Kepala (HIC_{15}, HIC_{36}) dan momen leher (NM) yang didapati ialah 47%, 49% dan 85% atas ambang NHTSA , manakala tenaga leher atas dan pemesongan dada didapati dalam lingkungan julat yang boleh diterima.

Teknik yang dibangunkan dalam kajian ini boleh diguna pakai untuk membangunkan model FE dami pelbagai saiz daripada model dami nahas yang sedia ada. Model kepala biofidelik boleh digunakan untuk menganggar kecederaan daripada nahas kenderaan disebabkan kontak kepala dengan bahagian dalam kenderaan dan ketinggian terjatuhnya kemalangan untuk pelbagai lokasi kepala.

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I certify that a Thesis Examination Committee has met on 3 April 2017 to conduct the final examination of Ibrahim Abdullahi Rafukka on his thesis entitled "Development of Three-Year Old Nigerian Numerical Child Dummy Model for Vehicle Safety Assessment" 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 Doctor of Philosophy.

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Zulkiflle bin Leman, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Faizal bin Mustapha, PhD
Associate Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Zaini Ahmad, PhD
Senior Lecturer
Universiti Teknologi Malaysia
Malaysia
(External Examiner)

Elsadig Mahdi Ahmed Saad, PhD
Professor
Qatar University
Qatar
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 2 June 2017

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment 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)

Nuraini Bint Abdul Aziz, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Manohar A/L Arumugam, PhD
Professor
Faculty of medicine and Health Sciences
Universiti Putra Malaysia
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Professor and Dean
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Name of Member of Supervisory Committee: Associate Professor Dr. Nuraini Bint Abdul Aziz

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Name of Member of Supervisory Committee: Professor Dr. Manohar A/L Arumugam

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LIST OF ABBREBIATIONS AND NOTATIONS

ATD	Anthropometric Test Device
3YO NC	Three year old Nigerian child
3YO HIII	Three year old Hybrid III
6YO HIII	Six year old Hybrid III
LSTC	Livermore Software Technology Corporation
NM	Neck Moment
NHTSA	National Highway Traffic Safety Administration
AIS	Abbreviated Injury Scale
CoG	Centre of Gravity
CRS	Chid Restraint System
FE	Finite Element
MGRS	Multicenter Growth Reference Study
UMTRI	University of Michigan Transportation Research Institute
HIC	Head Injury Criteria
CT	Computer Tomography
CRABI	Child Restraint Air Bag Interaction
OC	Occipital Condyle
FMVSS	Federal Motor Vehicle Safety Standard
FTSS	First Technology Safety System
TBI	Traumatic Brain Injury
THUMS	Total Human Body for Safety
CAD	Computer Aided Design
PMHS	Post Mortem Human Subjects
LATCH	Lower Anchors and Tethers for Children

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SAE	Society of Automotive Engineers
NCAC	National Crash Analysis Centre
RSM	Response Surface Method
HIC_{36}	Head Injury Criteria in 36 ms windows
HIC_{15}	Head Injury Criteria in 15 ms windows
HD	Head depth
HH	Head height
HB	Head breadth
CL	Characteristic length
CFC	Channel Frequency Class
N_{ij}	Neck Injury Criteria
M_{oc}	Moment about Occipital Condyle
M_y	Neck moment about y-axis
D_{HIII}	Morphed three year old Hybrid III dummy FE model
D_{Nig}	Morphed three year old Nigerian child dummy FE model
E	Elastic modulus
ϑ	Poisson's ratio
ρ	Mass density
G_o	Short term shear modulus
G_1	Long term shear modulus
K	Bulk modulus
β	Decay constant parameter

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Road traffic accident claimed about 1.2 million lives annually worldwide; hence it is considered to have high impact on the health and development of any society (WHO 2013). It is high in developing countries because of weak safety regulations and poor infrastructures. As the developing nations build more roads and get more access to motor vehicles, road traffic accident will keep increasing in the future (Rivara 2009). It has been forecast that traffic fatalities will increase by 55% by the year 2020. Great attention has been given to road safety recently by international community in taking into account 2030 agenda for sustainable development, in which road traffic accident was set to reduce by 50% in 2020. This fact shows the recognition of the contribution of road safety to health. Economically however, it was shown that road traffic accident in low and middle income countries causes a loss of about 5% of GDP (WHO 2013).

As the number of cars used on the road increased, the number of children involved in road traffic accident has also increased. Today, road traffic accidents are considered to be a major public health problem worldwide. In developed countries it was reported to be the most common cause of fatalities to children (Bauer & Stelner 2009).

Figure illustrates that road traffic accident is the major cause of injuries to children aged 0 to 17 years worldwide.

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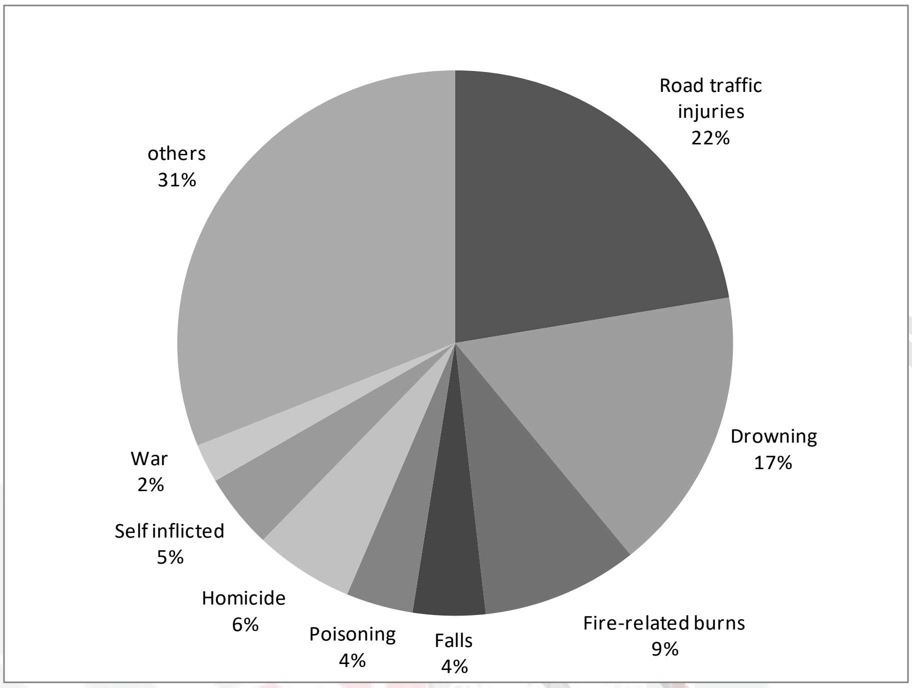

Figure 1.1 : Distribution of global child injuries for 0-17 years old world wide for 2004 (Peden & Oyegbite 2008)

Child vehicle safety has been given much concern recently by vehicle developers and researchers with particular attention to design of biofidelic child dummies and Child Restraint Systems (CRS). Despite the occupant safety systems available, child protection in vehicle crashes still remains unfavourable.

Crash dummies, also known as anthropometric test device (ATD), are tools used to test the safety performance of vehicle and also to predict the effectiveness of safety systems such as seat belt, CRS and air bag in protecting the occupant in the event of crash. ATDs are available representing adult and children of various ages. These crash dummies are designed for 50^{th} percentiles of some ages, thus leaving out small and bigger percentiles. For the ATD to become reliable tool in injury assessment it must be designed based on the real human being anthropometry and biomechanical response. Current ATDs are designed to represent United States, Europe and Japan children population. It was learnt that variability in anthropometry of various population around the world has not been considered in crash dummy development. Recent anthropometric study by Natale & Rajagopalan, (2014) compares weight, height and head circumference of infants for 55 countries around the world. Weight for example, was found to vary among different national and ethnic groups for 2 years old child as shown in Figure 1.2. Children of some countries are out of the WHO's Multicenter Growth Reference Study (MGRS). It is therefore important to consider anthropometric variations in crash dummy and CRS design.

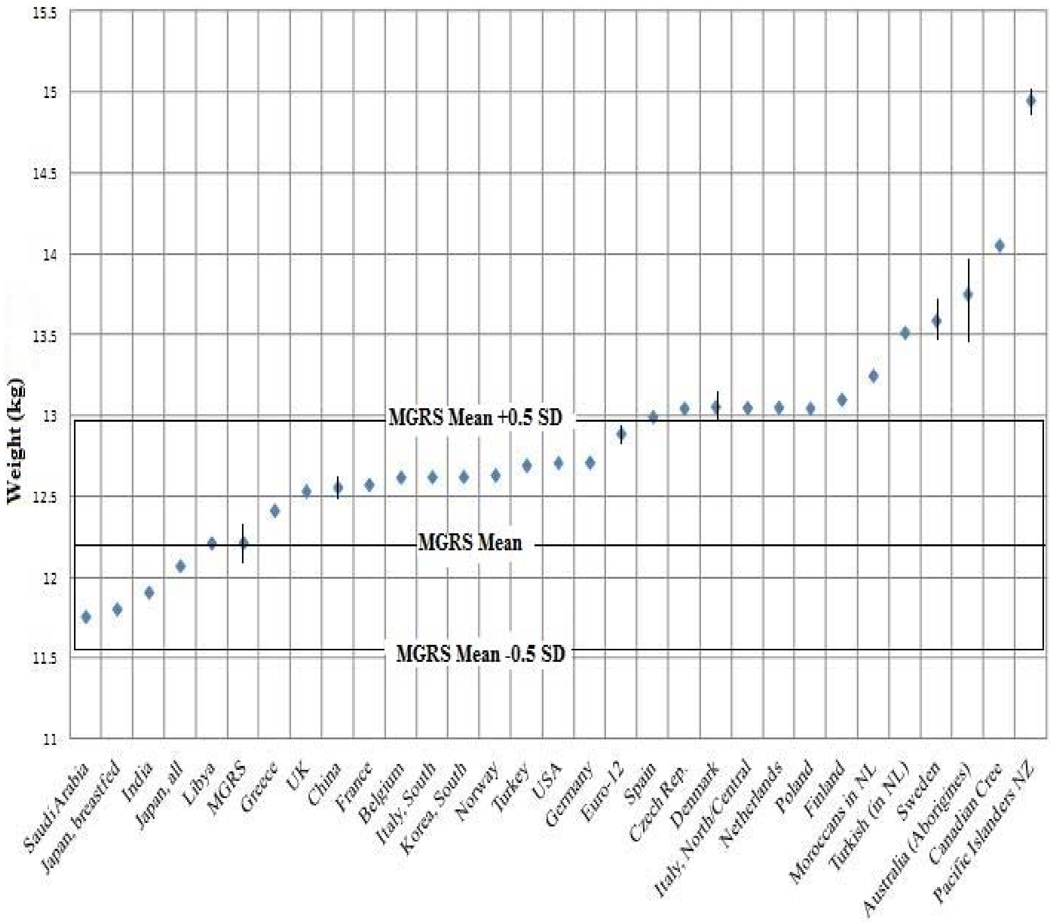

Figure 1.2 : Weight at 2 year of 30 countries in comparison with MGRS scale mean (Natale & Rajagopalan 2014)

Nigeria being the African most populous country, has been reported to have the highest road traffic accident rate in Africa, and second in the world (Atubi 2010; Ukoji 2014). Developing child dummy to represent this population in vehicle crash test is therefore important considering the possible mismatch between the child and the current crash dummies due to differences in anthropometries. Average three year old Nigerian child weight for instance was reported to be below WHO standard (Aina & Morakinyo 2001). Thus their biomechanical response is expected to be different from the traditional child crash dummies.

For a given vehicle design, the severity of injury in vehicle occupant is highly dependent on physical sizes, age and weight of occupant. In the effort to keeping vulnerable population safe in vehicular crashes, research on crash dummy development was recently focused on children especially obese, elderly, and pregnant women, with little attention to the variation in children anthropometry.

Finite element (FE) models of crash dummies have recently become the tool in vehicle crash test and safety systems evaluation because of their economic, technical and ethical advantages. Analysis of crash injuries is now done with finite element methods due to its affordability and accuracy. Human body models are modelled with their sizes, weight and material properties to represent the real human being. Though, there are FE models of three year old (3YO) child developed by Livermore Software Technology Corporation (LSTC) and Humanetics, these models were developed based on anthropometry of some specific populations and for only 50th percentiles.

Furthermore, child dummy head is the most important body segment in injury prediction, because it is the body region that needs extra protection for children of all ages (Andersson 2012). Figure 1.3 indicates that head has the highest percentage of injury in motor vehicle crashes. About 50% of the injuries sustained by child occupants in crash events are on the head. This signifies the importance of accurate biofidelic head model that will measure the response of the head for various impact directions for use in the vehicle safety systems assessment, playground designs as well as forensic applications.

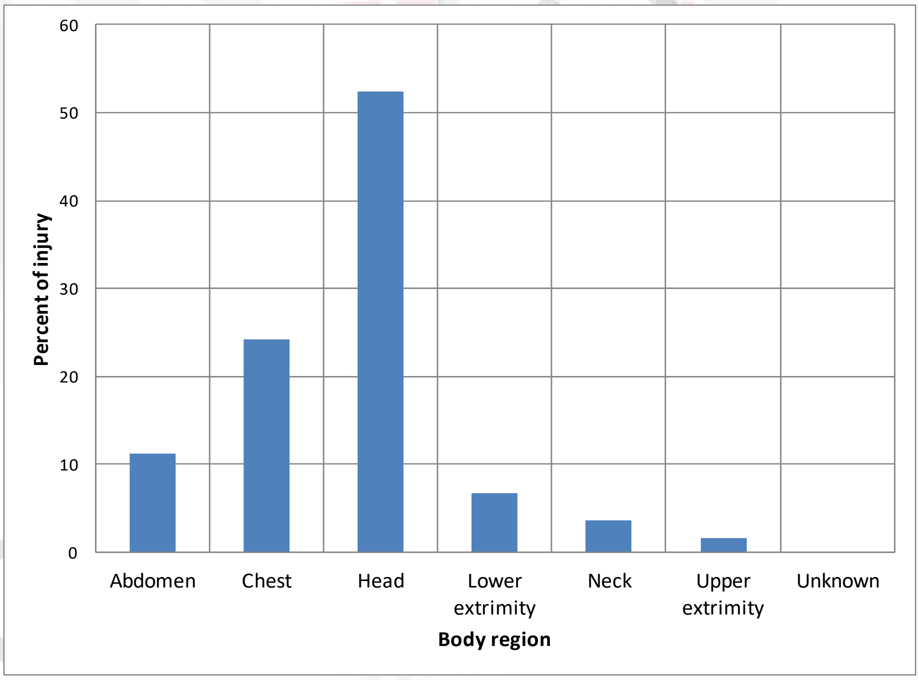

Figure 1.3 : Percentage of Passenger Vehicle Occupant AIS 3 - 6 Injuries, Age 0 - 8 Years Old, by Injured Body Region (Starnes & Eigen 2002)

Head injury is a calamity that causes death of vehicle occupants of all age groups. The trauma is more destructive to children, whose centre of gravity (CoG) is higher relative to their body height making them susceptible to head-first fall. Motor vehicle crash, pedestrian collision, falling on playgrounds and shaking-impact syndrome are some of the causes of traumatic brain injury (TBI) to children. Thus to investigate the injuries severity of child's head on impact a biofidelic head model capable of predicting biomechanical response is necessary. Lack of paediatric cadaver data because of ethical reasons makes it very hard to validate the head models for various impact locations.

1.2 Problem statement

Current vehicle design relies on the crash tests for the assessment of vehicles crashworthiness and occupant protection systems. Unfortunately, the crash test uses ATDs that represent few sizes, mainly 50th percentiles, thereby leaving obese and slim children, like those of most African countries, out of coverage. Poor representation of this population by current crash dummies in anthropometric and biomechanical variation, made the ability of safety systems to effectively protect the vulnerable population very difficult to assess. Three year old Hybrid III (3YO HIII) dummy was developed using the only recent comprehensive anthropometric data of children which was collected in 1970's by University of Michigan Transportation Research Institute (UMTRI). This form the basis of most United States current child body dimensions (Crandall et al. 2012). On the other hand, Q-dummies series, are designed by utilizing the combined anthropometry of United States, Europe and Japanese (CANDAT DATABASE) (Wismans et al. 2008). These crash dummies represent only the 50th percentiles of the population they represent. Non standard child dummies such as 5th and 95th percentiles are equally needed for crash analysis, since they cannot be represented by 50th percentile dummy. Efforts made by researchers in developing dummies to represent a given population is mainly on adult (Happee et al. 1998; Kim & Son 2003) with little attention to children, despite the studies reported differences in anthropometry between children of different population and crash dummies (Serre et al. 2006). Injuries severity in vehicular crashes were shown to depend on the child anthropometry (Kim et al. 2015). Hence there is a need to create a method of developing FE dummy models for various populations from the existing ones.

Furthermore, the main cause of head injury during impact is contact with the car interior such as front seat, back seat and doors panel and windows (Giordano & Kleiven 2016). It therefore important for crash dummies to estimate injuries for various head locations. The current crash dummies were developed with their heads validated using scaled adult cadaver data and mostly for side and frontal impact applications only. Crash dummy FE models are developed to represent physical crash dummies: hence their responses are usually validated against respected certification corridors. While these corridors were developed based on human cadaver data for adults, children models have normally been validated against scaled adult biomechanical response, despite the differences in size and material properties, because of lack of child cadaver data for ethical reasons. Lack of data of children also restricts design of dummies that can measure injuries of various head locations. Limited effort was made in validating the crash dummy heads against child cadaver data. Until recently, by Loyd, (2011), in the Hybrid III family, only 50th percentile adult was validated against cadaveric data from Hodgson & Thomas, (1971) for frontal impact but none of child ATDs was compared against human data (Loyd et al. 2012a). Despite the need to predict injuries for various child head locations, current crash dummies are only capable of estimating frontal and side impacts. To the best of the author's knowledge, no study was carried out on extending the application of current

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ATD heads to measure impacts from heads locations such as occipital and vertex for the estimation of injuries due to contact with vehicle interior during crash

Research on injury mitigation for child occupants is currently focused on the improvement of child seat and anchorages used to fix the seat to the vehicle (Hu et al. 2008; Hu & Mizuno 2009; Kapoor et al. 2008; Loyd et al. 2012a). A child seat FE model developed for child of given size and weight is important. FE model of Bebe Comfort seat was modelled and validated for application in FE crash test using 3YO NC dummy.

1.3 Objectives

The purpose of this work is to develop a three year old Nigerian child (3YO NC) dummy FE model using 6YO HIII child dummy FE model as a reference. The technique described in the work can simplify development of FE dummy models of various anthropometries, hence enable other non-standard size dummies to be modelled. Biofidelity of head FE model was improved to enable a more accurate injury prediction of various head impact locations. Crash test analysis was conducted using 3YO NC dummy in 1992 Ford Taurus FE model. The main objectives of the study are:

- To develop method of scaling child ATD finite element model to a specific target anthropometric dimension and apply the method in developing and validating three year old Nigerian child dummy FE model.
- To develop 3YO Nigerian child dummy head model material properties to predict injuries of various head locations
- To determine the crashworthiness characteristics of car FE model using the developed 3YO child FE dummy model, and assess its safety performance in reference to NHTSA recommended limits.

1.4 Scope and limitation of work

The scope of this work includes development and validation of 3YO NC crash dummy model by morphing a 6YO HIII dummy model, and validation of head model against scaled child cadaver data for various head impact locations. The work also considered improvement of 6YO HIII dummy head model for lateral impact assessment, design of CRS FE model for three year olds and evaluation of vehicle crashworthiness with developed child model. The limitations of this study are as follows:

- A comprehensive anthropometry data of three year old Nigerian child was not obtainable because of diversity of tribe and living status. The data used in the study was obtained by preliminary survey taken from a government hospital in Nigeria; a small size sample was used.
- Unavailability of Nigerian child cadaver test data to validate the model at component and full dummy levels. Hence, the dummy model was validated by

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comparing its response with cadaver data from literature, certification corridors and other three years old child physical and FE dummy models.

1.5 Highlight of work contribution

The contribution of this work to the body of knowledge includes:

- A new method of scaling child dummy finite element model to specific anthropometry. This technique reduces the time and cost of developing child dummy FE model from the physical crash dummies and allow for developing dummy of various sizes.
- Determination of 3YO NC anthropometric data for use in child dummy modelling and other ergonomics applications.
- Development and validation of 3YO child dummy FE model for Nigerian population. This is first attempt to create dummy model with size suitable for African population.
- Development of three year old child dummy head model for the prediction of head injuries in various impact locations.
- Upgrading the 6YO Hybrid III dummy head model for side impact application. The improved head model could serve as free motion head form for 6 year olds since it is not available in LSTC website.
- Development of child restraint seat to accommodate Nigerian child FE model for finite element crash analysis
- Evaluation of safety performance of 1992 Ford Taurus FE model with respect to child vehicle occupant at 48 km/h.

1.6 Thesis layout

This thesis is made up of six chapters. It starts with chapter 1 which describes the problem and the need for the project as well as mentioning the objectives outline. Chapter 2 presents the literature review on the human anatomy as related to automotive design, crash dummy FE modelling and testing methods, morphing technique in dummy modelling, anthropometry in crash dummy design, crashworthiness of cars with respect to child occupant injuries, as well as theoretical overview of finite element method and LS-DYNA material models. Chapter 3 contains the methodology of research work, anthropometric data collection, child dummy modelling and validation as well as design of CRS and crash analysis of car finite element model using developed child model. The simulation results for the validation of dummy FE model at segment and complete dummy level was presented in chapter 4. Chapter 5 presents the results of CRS validation and application of child dummy in vehicle crashworthiness test. Finally, the thesis ends with conclusions and recommendations for future works in Chapter 6.

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