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Active Child Models for Traffic Safety Research

Interim Report 1, October 2012

LAURE-LISE GRAS, KARIN BROLIN

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ABSTRACT

The project Active Child Models for Traffic Safety Research is funded by Folksams Forskningsstiftelse. The overall aim is to increase the safety of child car occupants and thereby reduce the number of traffic induced injuries in 3 to 12 year-old children. This will be done by creating a computer model of a child that includes active musculature. The model will be used to reproduce emergency manoeuvres with biofidelic response at low acceleration levels. Literature on child safety has been reviewed with a main focus on child numerical models. Very few child models exist and for most of them, their response is validated against Anthropometric Test Devices (ATDs) certification corridors and not paediatric data. Models of children and child sized ATDs are either finite element or multi body models. Finite element models are more likely to predict injuries and contacts, whereas multi body models can preferably be used to reproduce kinematics in long duration events like emergency manoeuvres. Because of this, it has thus been decided to first work with child multi body models in the MADYMO code (TASS, Rijswijk, the Netherlands). The models that will be studied are the 6 and 10 year-old child facet models and the Q6 and Hybrid III 6 year-old ATDs available in MADYMO as well as the 6 year-old pedestrian model previously developed by Jikuang Yang at Chalmers University of Technology. Simulation activities have been planned and the models' responses will be analysed and compared with kinematics data of child volunteers in emergency manoeuvres and sled tests. Then, based on their performance, one model will be chosen to implement active musculature. Extra experimental data for tuning and validation of the model may be required. As a consequence, new experiments on child volunteers are planned, including the acquisition of muscular activity. The model response will be compared to those results. Based on the active child multi body model capability to reproduce pre-crash events, it will be discussed and decided in January 2013 whether to continue with a multi body model or start the same process with a finite element model. In the long term, the active child model will be used to reproduce both pre-crash and in-crash events and help understanding the protective principles of forward facing children and how they interact with current and future vehicle safety systems and child restraints.

Keywords: Active behaviour, Child, Muscle, Numerical model, Pre-crash event

Contents

1 Introduction

The overall aim of this project is to increase the safety of child car occupants and thereby reduce the number of traffic induced injuries in 3 to 12 year-old children. Specifically, this will be done by creating a computer model of a child that includes active musculature and that can complement the on-going research with volunteer data.

The first aim with this numerical active child Human Body Model (HBM) is to reproduce pre-crash events with biofidelic response at low acceleration levels. This will be done by comparing the model response with the response of child volunteers in emergency manoeuvres (Stockman, 2012).

The second aim is to simulate pre-crash events at load levels that cannot be performed with child volunteers. The child HBM will then be used to understand the protective principles of forward facing children and how they interact with current and future vehicle safety systems and child restraints.

2 PROGRESS

This chapter gives an overview of the progress and activities within the project from March until October 2012. In January and February only administrative task for recruitment of a post-doc was performed by Karin Brolin.

Laure-Lise Gras was given the post-doc stipend financed by this project. She obtained her PhD on 2011-12-05 with a thesis titled “Characterization of muscle mechanical properties at various strain rates” at Arts et Métiers ParisTech, France. She was able to start the work at Chalmers on March 12, 2012. The stipend duration is 2012-03-12 until 2013-04-11, and will be extended to 2014-03-11 when the second year funding is granted by Folksams Forskningsstiftelse.

2.1 MARCH - JUNE

The first month was mainly used to orient Laure-Lise Gras about the on-going projects, especially the child safety research at SAFER and the FFI project on active human modelling. Then, the literature was reviewed on the topic of child safety in general and specifically on the different child numerical models that are available. The literature review report is included as a separate chapter in this interim report, see Chapter 3.

The computational software identified to be of interest in this project is MADYMO (TASS, Rijswijk, The Netherlands) and LS-DYNA (Livermore Software Technology Corporation, Livermore, California, US). MADYMO is a software for multi body dynamics and suitable to reproduce the pre-crash kinematics. LS-DYNA is a software for finite element analyses, commonly used by the automotive industry for crash simulations. It is capable of simulating contacts and is used in the human body modelling projects at SAFER. A decision has been taken to start with the MADYMO software and by January 2013 make a decision to either continue with MADYMO or change to LS-DYNA. This is also a question of child model availability.

2.2 JULY - OCTOBER

Activities to get familiar with the MADYMO software, starting with the 6 year-old facet model, were performed. In parallel, communication with TNO and TASS, (distributors of MADYMO) is on-going to explore possibility for collaboration and access to the TNO model with an active spine. Also, work to adjust the Chalmers' 6 year-old pedestrian child models by Liu and Yang (2002) to occupant models has been initiated. Models developed with MADYMO will be used to reproduce the behaviour of children in emergency manoeuvres, with volunteer data from the studies by Stockman (2012) and Bohman et al. (2011).

The plan for the simulation activities and the current and future work is presented in Chapter 4. A timeline until March 2014 with the next steps is also provided in Chapter 5.

3 Literature review

This chapter reviews available numerical models of 3-12 year-old children and of corresponding numerical models of Anthropomorphic Test Devices (ATDs). After an introduction, the different models are presented in two groups: the finite element models and the multi body models. Code and software, geometry, mechanical properties, validation and applications of these models are described and then discussed. The models found in the literature and some unpublished models are listed by child age in Tables 1 – 3. No 12 year-old models were found in the literature. There are models of a 5th percentile female, which corresponds to a 12 year-old child, however they are not discussed in this report.

3.1 Introduction

The protection of children in motor vehicle crashes has increased with the use of child restraint systems, however, car crashes are the second leading cause of death for children between 5 and 14 years old (World health organization, 2009). Child occupant fatalities and injuries occur mostly in frontal and side impacts for children seated in passenger vehicles (Final Rule, Federal Motor Vehicle Safety Standards 213, Child Restraint Systems, 2003). The head is the most frequently injured body region for forward facing children. To understand how children are injured, Bohman et al. (2011) studied the causation scenarios of head injuries in frontal impacts for rear-seated, restrained children. They concluded that contact with the car interior, like the back of the front seat, the door panel, or the window was the principal cause of head injuries. They also found that emergency manoeuvres like braking, steering or a combination of both influenced the kinematics of children before the impact and thus to affect the child interaction with the restraint systems. Consequently, there is a need to improve child protection and evaluate the restraint systems in use today for emergency manoeuvres.

Child ATDs are common tools to evaluate child restraint systems in car crash situations. They are surrogates designed to represent children of different age groups in impact situations. Two main ATD series are available: the Hybrid III and the Q series. The Hybrid III series is composed of 3, 6 and 10 year-old children. The Q series represent 0, 1, 1.5, 3, 6 and 10 year-old children. For each ATD, the anatomical representation of body regions with regards to size and weight is based on child anthropometry databases. For instance for the Q series, the CANDAT database, with anthropometry data collected in US, Europe and Japan, was used. The biomechanical response of child ATDs is based on scaled data obtained from experiments performed with adult post mortem human subjects in crash conditions. Certification tests are required such as thorax impact test and the ATD response should fit experimental corridors scaled down from adult results. These data are the only available data for child ATDs since very few paediatric tests have been performed. Scaled down mechanical properties is the main limitation of child ATDs. ATDs are equipped with sensors to register their response during impacts. These impact conditions are defined in safety regulations. In Europe, the regulation UNECE R44 regarding child restraint systems recommends specific sled tests for different impact conditions. For instance a child restraint system in a frontal impact is evaluated at a velocity of 50 km/h and a maximum acceleration of 28 g. For a rear-impact, the velocity decreases to 30 km/h and to a peak acceleration of 21 g. These experimental protocols allow designers of child restraint systems to make sure their restrains will be efficient in these configurations.

Table 1: List of 3 year-old child and ATD models.

FE: finite element model; MB: multi body model. Occ: occupant; Ped: pedestrian. Codes: MADYMO (TASS, Rijswijk, The Netherlands), LS-DYNA (Livermore Software Technology Corporation, Livermore, California, US), PAM-CRASH (ESI Group, Paris, France), RADIOSS (Altair Engineering Inc, Troy, Michigan, US), and ABAQUS (Dassault Systems, Vélizy-Villacoublay, France). /=Not known.

Model name in this report	**FE/MB**	**Code**	**Occ/Ped**	**Validation**	**Reference**	**Page**
CHILD						
Koizumi (2005)	FE	MADYMO	Occ	ATD certification test: thorax	Koizumi et al. 2005	9
Mizuno (2005)	FE	LS-DYNA	Occ	ATD certification test: neck, thorax, spine Volunteer tests: abdomen	Mizuno et al. 2005	9
Mizuno (2006)	FE	LS-DYNA	Occ	ATD certification test: pelvis	Mizuno et al. 2006	10
Zhang (2009)	FE	LS-DYNA	Occ	Paediatric cadaver tests: cervical spine	Zhang et al. 2009	10
Digital Child Project 3YO	FE	/	/	/	www.uab.edu/scib	11
CASPER 3YO	FE	/	Occ	/	www.casper-project.eu	12
MADYMO Child 3YO Facet	MB	MADYMO	Occ	/	Van Rooij et al. 2005	12
Liu (2002) 3YO	MB	MADYMO	Ped	Reconstruction of road accidents, brake deceleration: 0.7 g	Liu and Yang 2002	12
Van Hoof (2003) Child 3YO Ellipsoid	MB	MADYMO	Ped	Validation of the 50th percentile male	Van Hoof et al. 2003	12
ATD						
Humanetics Hybrid III 3YO	FE	LS-DYNA PAM-CRASH	Occ	ATD certification tests	www.humaneticsatd.com	10
Tot (2009) Hybrid III 3YO	FE	LS-DYNA	Occ	Paediatric cadaver tests: cervical spine	Tot et al. 2009	10
Humanetics Q3	FE	LS-DYNA PAM-CRASH	Occ	ATD certification tests	www.humaneticsatd.com	10
Humanetics Q3S	FE	LS-DYNA PAM-CRASH	Occ	ATD certification tests	www.humaneticsatd.com	10
Dynamore P3	FE	LS-DYNA	Occ	ATD certification tests	www.dynamore.de	10
MADYMO Hybrid III 3YO	MB	MADYMO	Occ	ATD certification tests	MADYMO Models manual	13
MADYMO Q3	MB	MADYMO	Occ	ATD certification tests	MADYMO Models manual	13
MADYMO P3	MB	MADYMO	Occ	ATD certification tests	MADYMO Models manual	13

Table 2: List of 6 year-old child and ATD models.

FE: finite element model; MB: multi body model. Occ: occupant; Ped: pedestrian. Codes: MADYMO (TASS, Rijswijk, The Netherlands), LS-DYNA (Livermore Software Technology Corporation, Livermore, California, US), PAM-CRASH (ESI Group, Paris, France), RADIOSS (Altair Engineering Inc, Troy, Michigan, US), and ABAQUS (Dassault Systems, Vélizy-Villacoublay, France). /=Not known.

Model name in this report	FE/MB	Code	Occ/Ped	Validation	Reference	Page
CHILD						
Digital Child Project 6YO	FE	/	/	/	www.uab.edu/scib	11
CASPER 6YO	FE	/	Occ	/	www.casper-project.eu	12
Okamoto (2003)	FE	PAM-CRASH	Ped	/	Okamoto et al. 2003	11
MADYMO Child 6YO Facet	MB	MADYMO	Occ	No validation	MADYMO Human models manual	12
BOBBY 6YO	MB	/	Occ	/	Huang et al. 2004	13
Liu (2002) 6YO	MB	MADYMO	Ped	Reconstruction of road accidents	Liu and Yang 2002	12
Van Hoof (2003) Child 6YO Ellipsoid	MB	MADYMO	Ped	Validation of the 50th percentile male	Van Hoof et al. 2003	12
ATD						
Humanetics Hybrid III 6YO	FE	LS-DYNA PAM-CRASH	Occ	ATD certification tests	www.humaneticsatd.com	12
Humanetics Q6	FE	LS-DYNA PAM-CRASH RADIOSS ABAQUS	Occ	ATD certification tests	www.humaneticsatd.com	12
MADYMO Hybrid III 6YO	MB	MADYMO	Occ	ATD certification tests	MADYMO Models manual	13
Sherwood (2003) Hybrid III 6YO	MB	MADYMO	Occ	Frontal impact: 49 km/h, 22 g	Sherwood et al. 2003	14
Hu (2012) Hybrid III 6YO	MB	MADYMO	Occ	Frontal impact: 23 g	Hu et al. 2012	14
MADYMO Q6	MB	MADYMO	Occ	No validation	MADYMO Models manual	13
MADYMO P6	MB	MADYMO	Occ	ATD certification tests	MADYMO Models manual	13

Table 3: List of 10 year-old child and ATD models.

FE: finite element model; MB: multi body model. Occ: occupant; Ped: pedestrian. Codes: MADYMO (TASS, Rijswijk, The Netherlands), LS-DYNA (Livermore Software Technology Corporation, Livermore, California, US), PAM-CRASH (ESI Group, Paris, France), RADIOSS (Altair Engineering Inc, Troy, Michigan, US), and ABAQUS (Dassault Systems, Vélizy-Villacoublay, France). /=Not known.

Model name in this report	**FE/MB**	**Code**	**Occ/Ped**	**Validation**	**Reference**	**Page**
CHILD						
Digital Child Project 10YO	FE	/	/	/	www.uab.edu/scib	11
MADYMO Child 10YO Facet	MB	MADYMO	Occ	No validation	MADYMO Human models manual	12
ATD						
Humanetics Hybrid III 10YO	FE	LS-DYNA RADIOSS	Occ	ATD certification tests	www.humaneticsatd.com	12
Humanetics Q10	FE	LS-DYNA PAM-CRASH	Occ	ATD certification tests	www.humaneticsatd.com	12
MADYMO P10	MB	MADYMO	Occ	ATD certification tests	MADYMO Models manual	13

However, in such configurations the child ATDs are placed in a standard position and are restrained according to protocols. The influence of an emergency manoeuvre on the sitting position or on the interaction of the child ATD with the restraint system is not taken into account. Moreover, children move a lot and this active behaviour cannot be assessed with child ATDs. As a consequence, knowledge of the child kinematics and behaviour in emergency manoeuvres or low acceleration events is needed in order to improve child safety.

Low acceleration experiments have been performed to investigate child kinematics. Arbogast et al. (2009) evaluated the kinematic response of the head and spine of both children and adults in sled tests. The same test set up was used by Seacrist et al. (2010) to compare the response of children with the Hybrid III 6 year-old ATD. In both experiments, a low severity frontal impact was reproduced, the velocity of the sled was about 8.3 km/h and the peak acceleration was around 3.5 g. The results highlighted differences between children and adults and between children and the ATD. Children had a higher forward excursion compared to both adults and ATD because of a more flexible spine. The children experienced greater head angular velocity than adults but less than the ATD. The difference between children and adults is explained by anatomical differences such as a proportionally larger head and smaller neck structure for children compared to adults. The authors concluded that the two main factors contributing to the difference in child kinematics were the mechanical properties of the tissues and the geometry of the skeleton. One limitation of these studies is the experimental environment. Even though children were restrained with a three-point seat-belt, they were not seated on a car seat or a child restraint system, thus leading to less realistic conditions.

Real-world driving studies give feedback on how children behave within the car and how they interact with the child restraint systems. Andersson et al. (2010) observed the position of the torso and head of children restrained on two different booster cushions with backrest and head side support during normal driving. They found that the child torso was positioned between the side supports in both booster seats, that shoulder to booster backrest contact was maintained on average 45% to 75% of the riding time depending on the booster design and that the head was in front of the head side support more than half of the riding time. Because of this latter sitting position, it was concluded that the child restraint system may be less efficient in case of side impact and lead to head impact with the front seat in case of frontal impact. The position of the moving child relative to the child restraint system is an important factor.

Emergency manoeuvres with child volunteers have been performed to look at the kinematics of children and their interaction with the shoulder belt when seated and restrained on different systems in the rear seat. The children were exposed to a steering manoeuvre (Bohman et al., 2011) and a braking manoeuvre (Stockman et al., 2012). The steering manoeuvre was performed at 50 km/h and the maximum lateral acceleration was around 1 g. For the braking manoeuvre, the car was driven at 70 km/h and braked to a full stop, resulting in a maximum longitudinal deceleration of 1 g. Children were divided in two groups: a short group (stature of 105 – 125 cm) and a tall group (stature of 135 – 150 cm). Children of the short group were seated on a booster cushion with a backrest and then on a booster cushion without a backrest. Tall children were seated on a booster cushion without a backrest and then directly on the car seat. Tall children had a less lateral displacement in the steering manoeuvre and a less forward displacement in the braking manoeuvre than short children. Moreover, differences were observed regarding the shoulder belt position during the events. For short children and during the steering manoeuvre, the belt was maintained on the shoulder when they were restrained on a booster cushion with a backrest, whereas the belt was more likely to slip off the shoulder when they were on a booster cushion without a backrest. On the contrary, tall children managed to maintain the belt on their shoulder in all cases, by slightly moving their shoulder upward. For the braking manoeuvre, one case where the shoulder belt slipped off the shoulder before the braking manoeuvre illustrated the importance of the shoulder belt position, since it resulted in a forward displacement that was 1.8 times greater than the mean forward displacement of the other children in the same group. It was concluded that kinematics of children is influenced by many parameters: the child restraint system and how the belt is positioned prior to the emergency manoeuvre, the size and age of the child, and possible age differences in the active muscle response of the children during the event.

Many parameters have to be evaluated and taken into account when dealing with child safety. There are for instance car related parameters, such as the child restraint system, the belt positioning or the velocity and acceleration levels, and child related parameters, like specific mechanical properties, anatomy, age, size, and muscular activity. One challenge is to identify the main parameters that will influence the injury risk for the children. Experiments with volunteers help understanding how these parameters affect the child response. However a high number of experiments would be required to evaluate each parameter independently and to study the interactions between parameters. A more cost and time effective solution is to perform numerical analysis instead of real experiments. For that purpose, models of the restraint systems, the car interior, and children are required.

Numerical models of the human body are increasingly used to simulate both pre-crash and in-crash occupant responses. Numerical human body models have geometries closer to the real human anatomy than ATDs. For instance the finite element model Total HUman Model for Safety (THUMS) (Toyota Motor Corporation, 2008) has internal organs with geometry based on medical imaging of a 50th percentile male. Usually, human body models represent the 50th percentile male, but scaling methods have been developed to extend the number of models to specific anatomies such as the 5th percentile female or the 95th percentile male (THUMS, MADYMO Human Models Manual, 2012, Thunnissen et al., 1994, Mertz et al., 1989) including changes in geometry and mechanical properties. The responses of the human body models can be more biofidelic than ATDs, when compared to experiments performed on post mortem human subjects in crash conditions (Vezin et al., 2001, Behr et al., 2003). Moreover, most ATDs and thus their numerical models are developed for impacts in one direction and are therefore limited to either frontal or lateral impacts, whereas detailed human body models can represent the human response to omnidirectional impacts if sufficiently validated. In addition, there are models that implement the active muscle response, such as the model by Östh et al. (2012). Human body models are either finite element (Behr et al., 2003, Mendoza-Vazquez, 2012, Östh et al., 2012, Tropiano et al., 2004) or multi body models (MADYMO Human Models Manual, 2012, Meijer et al., 2008). Finite element models are usually models with detailed geometry used for crash simulations. They allow a good simulation of contacts which can be of interest to model the interaction between the occupant and the restraint systems. However, computational time is long which decreases the model efficiency to describe emergency manoeuvres. On the other hand, multi body models have fast computational time which makes them suitable to reproduce pre-crash kinematics. Multi body models are relatively simple and easy to use but contact definition is complex. As a conclusion, human body models are relevant tools for the automotive field; nevertheless, these models mainly represent adults and not children.

Child numerical models remain sparse. Therefore, the objective of this literature review is to give an overview of the available numerical models of both children and child ATDs. Finite element and multi body models of the whole body are presented and compared for each age group. Pedestrians and occupant models are considered in this review, but the main focus is on occupants.

3.2 Finite element models

Koizumi et al. (2005) developed a 3 year-old child model in the MADYMO code. Geometry of the model was obtained by scaling down the 50^{th} percentile model proposed in MADYMO to a child geometry based on anthropometry data from the CANDAT database. Material properties of soft tissues were kept equal to those of adults. Bone material properties and joint stiffness were scaled down. Validation of the model was obtained by comparing its response with corridors used for the 3 year-old ATDs certification: frontal and lateral thoracic impact tests (pendulum test, velocity: 4.3 m/s and 6.7 m/s for fontal tests and 4.3 m/s for lateral tests). The model was used to reproduce the UNECE-R44 regulation fontal sled test (specific acceleration level and velocity are not specified).

Mizuno et al. (2005) developed a 3 year-old child model in the LS-DYNA code. Geometry was obtained by scaling down the THUMS 50^{th} percentile male (Iwamoto et al., 2002, 2003) to a 3 year-old child (Figure 3.1). The child anthropometry was based on data collected in the United States of America (Young et al., 1976). The material properties of bones, skin and torso were scaled from adult data. The mechanical characteristics of other tissues such as ligaments, tendons, cartilage, and viscera were those of the THUMS adult model. Validation of the model was obtained by comparing its response with corridors on child volunteers for the abdomen (lap belt loading) and with the Hybrid III 3 year-old physical ATD response in calibration tests for the neck (pendulum test on the thorax, acceleration: 230 m/s² during 20 ms), thorax (pendulum test on the thorax, velocity: 6 m/s) and spine (flexion test at 45 degrees). As an application, the response of the Mizuno (2005) model was compared to the response of the physical Hybrid III 3 year-old ATD in a frontal sled test according to the UNECE-R44 regulation (acceleration: 24.5 g, velocity: 50 km/h). A qualitative analysis showed higher spine flexibility for the Mizuno (2005) model and thus different kinematics response between the model and the ATD.

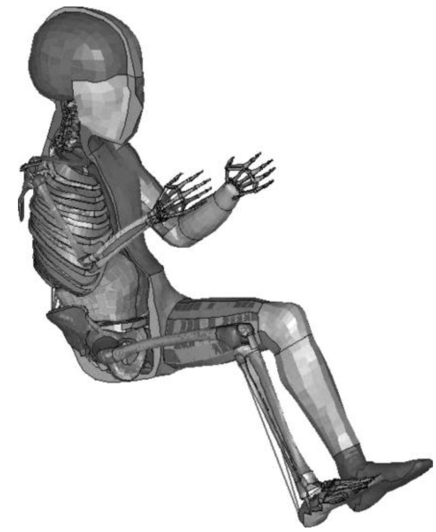

Figure 3.1 Three year-old child finite element model - Mizuno et al. 2005

Mizuno et al. (2006) proposed an improvement of the Mizuno (2005) 3 year-old child model in the same LS-DYNA code. The initial geometry of the pelvis was scaled from an adult pelvis which does not take the amount of cartilage and the shape of the iliac observed in children into account. As a consequence, in the Mizuno (2006) model, the shape of the pelvis iliac was modified and cartilage was added. The new geometry of the pelvis was based on medical imaging of a 5 year-old child. Material properties of bone and cartilage were the same as described in Mizuno et al. (2005). Validation of the model was obtained by simulating a pendulum side impact test according to the Q3 ATD certification protocol (impactor velocity: 5.2 m/s). The model was then used to reproduce the UNECE-R44 regulation frontal sled test (acceleration: 24.5 g, velocity: 50 km/h,) to evaluate different child restraint systems.

Zhang et al. (2009) also improved the Mizuno (2006) 3 year-old child model regarding the head and neck anatomy region. The geometry of the cervical spine was not changed. However, the mechanical properties of the ligaments, intervertebral discs and joints of the cervical spine were modified. The way these new mechanical properties were chosen is not described. Validation of the model was performed by comparing the head and neck response of the model with the response of reported paediatric cadaver head and neck complexes (2 to 7.5 year-old subjects) in flexion-extension bending (moment applied to T1 vertebra: ±2.4 N.m in 100 ms) and tensile tests (velocity applied to head centre of mass: 50 cm/s for 40 ms) (Ouyang et al., 2005). Comparison of the Zhang (2009) model with the Mizuno (2006) model was proposed by simulating a FMVSS 213 regulation frontal sled test (acceleration: 25 g, velocity: 42 km/h) and a fontal sled test performed on a paediatric cadaver (acceleration: 17 g) (Kallieris et al., 1976). Even though the head and chest accelerations were similar for the two models, the Zhang (2009) model had higher tensile and rotational properties and was more likely to predict cervical spine injuries like atlanto-occipital dislocation.

Dynamore Ltd developed a P3 child ATD model in the LS-DYNA code (www.dynamore.de). However this model has not been published.

Humanetics Ltd, former First Technology Safety Systems (FTSS) developed numerical models of child ATDs (www.humaneticsatd.com). Humanetics Hybrid III 3 year-old, Q3 and Q3S were developed to represent the 3 year-old ATDs. They are available in the LS-DYNA and PAM-CRASH codes. Geometry and mechanical properties of these numerical models are the same as for the physical ATDs.

Tot et al. (2009) modified the Humanetics Hybrid III 3 year-old model in the LS-DYNA code to improve the head and neck response. Geometry was the same as the original model; however the mechanical properties of the neck were modified. The initial elastic neck cable material was changed to a non-linear elastic material. The load-deflection characteristics of this new material were based on reported paediatric cadaver tests (Ouyang et al., 2005). Validation of this model was made by reproducing reported paediatric cadaver tests: a tensile test and a flexion extension bending experiment (Ouyang et al., 2005). These experiments are the same as those studied by Zhang et al. (2009) to improve the neck of the 3 year-old child model. The Tot (2009) model was also used to reproduce a reported sled test performed with a paediatric cadaver (acceleration: 17 g) (Kallieris et al., 1976). The Tot (2009) model gave a kinematic response closer to the cadaver response than the Humanetics Hybrid III 3 year-old model.

Child human body models and child ATDs models have mainly been used to evaluate child restraint systems in frontal impacts (Hu and Mizuno, 2009, Kapoor et al., 2008, 2010, Zhang et al., 2007, Turchi et al., 2004) or side impacts (Cui et al., 2012, Kapoor et al., 2010, Li et al., 2011, Sasaki et al., 2009) and to evaluate injury mitigation systems in side impacts (Andersson et al., 2012). The responses of the child human body models were often compared to the response of the child ATD models. The main result was the lack of spine flexibility for the ATD models compared to the child models. Some examples of these comparisons between child and ATD models are described in the next three paragraphs.

Kapoor et al. (2008) compared the head trajectories and head rotation in a frontal impact for the Mizuno (2006) child model, Humanetics Hybrid III 3 year-old and Humanetics Q3 models. The simulation reproduced a FMVSS 213 sled test performed at 42 km/h and with a maximum acceleration of 22 g. Results were found similar for the Mizuno (2006) child model and the Humanetics Q3 model but not for the Humanetics Hybrid III 3 year-old model. It was concluded that the Q3 model was more biofidelic than the Hybrid III 3 year-old model and was more likely to represent a child's response during an impact. However, this result was based on the response of the Mizuno (2006) child model validated mainly against ATDs certification corridors.

Zhang et al. (2007) compared the head trajectory of the Mizuno (2006) model with the response of a child cadaver and the Humanetics Hybrid III 3 year-old numerical model in a frontal sled test (acceleration: 17 g) (Kallieris et al., 1976). The child model response was closer to the cadaver response than to the ATD response. This result was explained by the increased neck flexibility of the child model. Moreover, the head rotation around the y-axis was 14° higher for the Mizuno (2006) model than for the Humanetics Hybrid III 3 year-old model. As a result contact between the chin and the chest was observed for the Mizuno (2006) child model but not for the Hybrid III 3 year-old model. This sled test was also used to evaluate the Zhang (2009) and Tot (2009) models. However, the results obtained for the child (Mizuno (2006), Zhang (2009)) and ATD (Tot (2009)) models were not compared.

Li et al. (2011) compared the response of three numerical models in near side and far side impacts (acceleration: 22 g) when properly or incorrectly restrained. These models were: the Mizuno (2006) model without an improved neck, the Zhang (2009) model with head and neck improvements and the Humanetics Q3S model. The Q3S model was found to over predict head and chest accelerations especially because of its rigid spine. Because of more biofidelic mechanical properties, the Zhang (2009) model exhibited higher head accelerations than the Mizuno (2006) model, but similar chest acceleration. The main difference between these models concerned the forces in the lower and upper neck that were lower for the Zhang (2009) model.

Okamoto et al. (2003) developed a 6 year-old child model. This model was a pedestrian model developed in PAM-CRASH code. Geometry of the model was based on magnetic resonance imaging scans of a child volunteer. However, only the lower limb was modelled. The upper body was rigid and its geometry was scaled down from adult data. Regarding the mechanical properties, no information was given by the authors. No validation or simulations were described with this model. However, it is worth noticing that this is the only model where the real anthropometry of the child was taken into account, instead of only relying on data scaled down from adults.

In order to improve the geometry and mechanical properties of child numerical models, the Digital Child Project proposed by the Southern Consortium for Injury Biomechanics started in 2006 (Pediatric Injury Biomechanics Book, 2013). Based on medical imaging, the 3, 6 and 10 year-old children were modelled with highly detailed geometries. A material properties database is being created. Simulations of cadaveric impact test were performed with the head and pelvis of the 10 year-old model

(Pediatric Injury Biomechanics Book, 2013), but no validation or applications of the whole models have been published yet.

The Child Advanced Safety Project for European Roads (CASPER) was proposed in 2009 to design new child numerical models with biofidelic characteristics. One task of the project consisted in collecting detailed geometries of body segments as well as internal organs based on the literature and medical imaging data. Material properties from the literature were also gathered. Based on these data, numerical models were created, but still some scaling methods were used to obtain the child geometries and mechanical properties. Models of 3 and 6 year-old children were developed, among others; however, as for the Digital Child Project, no validation or applications of these models have been published yet.

Regarding child ATDs, Humanetics Ltd proposes a Hybrid III 6 year-old model (LS-DYNA, PAM-CRASH), a Q6 model (LS-DYNA, PAM-CRASH, RADIOSS, ABAQUS), a Hybrid III 10 year-old model (LS-DYNA, RADIOSS) and recently a Q10 model (LS-DYNA, PAM-CRASH). Applications of these models were not found in the literature.

3.3 Multi body models

Liu and Yang (2002) developed child pedestrian models representing 3, 6, 9 and 15 year-old children using the MADYMO code. They were scaled down versions of the 50^{th} percentile male pedestrian model and composed of 15 ellipsoids linked together with 14 three-dimensional joints. The biomechanical properties were scaled from adult data for the joints properties but were also from child data for the parietal bone and ligaments. Validation of the child pedestrian models was done by reconstruction of road accidents (brake deceleration of 0.7 g).

Van Hoof et al. (2003) developed child pedestrian models representing 3 and 6 year-old children in the MADYMO code. Models were scaled down versions of the adult 50^{th} percentile male pedestrian model. Their anthropometric characteristics were based on the specifications of the Q ATDs (CANDAT database). Each model was composed of 64 ellipsoids and 52 kinematic joints. Mechanical properties were scaled down. Validation of the child pedestrian models was not provided directly; only the 50^{th} percentile male pedestrian model was validated by comparing different impact tests of the lower extremities, the pelvis, the abdomen, the thorax and the shoulder with post mortem human subjects. The adult model was also validated against full body car to pedestrian impact tests performed with post mortem human subjects, for instance impact with a car at 32 km/h and a deceleration of 4.7 m/s^2.

Van Rooij et al. (2004) used the Van Hoof (2003) 6 year-old model to reconstruct and evaluate pedestrian kinematics in a car to pedestrian collision (40 km/h, brake deceleration of 0.7 g). Forero Rueda and Gilchrist (2009) used the Van Hoof (2003) 6 year-old model with modified head contact characteristics to reproduce falls of children from a playground climbing frame. Untaroiu et al. (2010) developed optimization techniques with the same model, to simulate a child running in front of a vehicle. The limitations highlighted in these studies were the lack of accurate material properties in the literature to describe the response of for instance the head contact characteristics and the lack of muscular activity that could affect the kinematics of the child falling from the playground and the injury risks.

Van Rooij et al. (2005) developed a 3 year-old child occupant multi body model in the MADYMO code (Figure 3.2), as a facet model. Facet models representing 6 and 10 year-old children were also proposed in MADYMO (MADYMO Human Models Manual, 2012). The anthropometry was obtained by scaling the adult model to the specifications of the Q ATDs, similarly to development of the pedestrian models. The facet models consist of 92 bodies. The main differences compared to the ellipsoid models are the presence of a meshed skin, a deformable torso and a higher number of joints to model the spine. Each vertebra is represented by a joint to give a more flexible spine. Mechanical properties were scaled down from adult data. Validation of the child models has not been published.

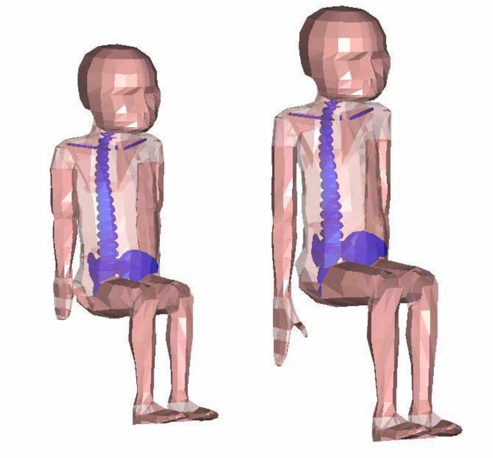

Figure 3.2 Child facet models - Van Rooij et al. 2005

A 6 year-old child model named BOBBY 6YO was reported in Haug et al. (2004). This model was an articulated rigid body model developed in the PAM-CRASH code. Geometry was scaled down from an 8 year-old child for the external geometry, and from an adult for the skeleton. However, mechanical properties and validation of the model has not been published.

Child ATDs models are proposed in MADYMO. The models used in the literature are the P series ATDs representing 3, 6 and 10 year-old children (Cao et al., 2010, Emam et al., 2005, Kapoor et al., 2005, Koplin Winston et al., 2000); the Q3 (Johansson et al., 2009, Kendall et al., 2009, Van Rooij et al., 2005), the Hybrid III 3 year-old (Surcel and Gou, 2005, Zhao et al., 2009) and the Hybrid III 6 year-old (Hu et al., 2012, Menon et al., 2007, Sherwood et al., 2003). The Q6 model is now available in the MADYMO code but there are no publications describing its use (MADYMO Model Manual, 2012).

These MADYMO ATD models are ellipsoid models. For instance the Hybrid III 3 year-old model is composed of 28 ellipsoids (Surcel and Gou, 2005) and the Q3 model of 32 ellipsoids. These models were validated at both a component level and at a whole body level (MADYMO Model Manual, 2012). They were used to study injury parameters such as cervical spine injuries, head and neck injury criteria (Kapoor et al., 2005, Sherwood et al., 2003), to evaluate child restraint systems (Johansson et al., 2009, Zhao et al., 2009) and different belt geometries (Menon et al., 2007). For instance, Emam et al. (2005) evaluated the differences in effectiveness of forward and rearward seats in frontal crash (acceleration: 14 g; velocity: 41 km/h) with the P3 model. Kendall et al. (2009) studied the same question in oblique crashes (acceleration: 27 g) and crashes after pre-impact braking (braking deceleration before crash: 0.7 g) with the Q3 model. It was demonstrated that rearward facing seats benefit children compared to forward facing seats.

Sherwood et al. (2003) developed a Hybrid III 6 year-old model with modified thoracic spine stiffness. This was done by adding a rotational joint in the model with a stiffness based on results from a cadaver test. Validation of the model has not been published. The modified model was used to show that the initial model was too stiff to properly reproduce the cadaveric response and thus over-predicted spinal injury.

Hu et al. (2012) developed a Hybrid III 6 year-old model with a modified pelvis and abdomen to simulate submarining, i.e. the belt loading the soft tissues in the abdomen instead of the pelvic bones. This new model was based on a physical Hybrid III 6 year-old ATD with an updated pelvis. Validation of the model was achieved by comparing the response of the model with the response of the physical ATD in sled tests with and without submarining (acceleration of 23 g).

3.4 Discussion

The objective of this literature review was to provide an overview of the available finite element and multi body models of 3 to 12 year-old children and child ATD models. Eighteen child and 18 ATD models were identified. Of these, 9 were models of the 3 year-old child, 7 of the 6 year-old child, 2 of the 10 year-old child, and no models of the 12 year-old child were found. For the ATD models, 8 represented the 3 year-old child, 7 represented the 6 year-old child, 3 represented the 10 year-old child, and no models represented the 12 year-old child.

Very few child models are available and not all age groups are represented. Regarding the finite element models, only the Mizuno (2005) 3 year-old model has been used and successively improved to increase its biofidelity in terms of mechanical properties for the neck (Zhang (2009) model) and in terms of both geometry and mechanical properties for the pelvis (Mizuno (2006) model). The Okamoto (2003) 6 year-old pedestrian model had better geometry characteristics but only for the lower extremity but its mechanical properties were not published. No available finite element models of the 12 year-old child were found in the literature. Child ATDs for the Hybrid III, Q and P series are represented for each age group: 3, 6 and 10 year-old, but not all of them were studied. For the multi body models, the child occupant models lack publications with validation data. The pedestrian models were more developed and used; however they are scaled down version of adult models with regards to both geometry and mechanical properties.

Many studies compare the responses of the child human body models' and child ATD models'. Beyond obvious geometry differences, the main difference between these two kinds of models was the spine flexibility. However, even though ATD models are stiffer than child human body models, all their mechanical and geometric properties are known and can easily be changed numerically (Tot et al., 2009, Sherwood et al., 2003, Hu et al., 2012). Parametric studies could be performed numerically to evaluate new materials or components shapes in order to have an efficient numerical tool or to improve the physical ATDs. However, if the numerical ATD is modified to better represent child volunteers or child cadaveric responses, it will no longer be a valid representation of the physical ATD.

Geometry and mechanical properties have to be improved in child computational models. Medical imaging can help improve the child human body models with a detailed geometry, taking into account the anatomical differences between children and adults, such as done for the pelvis in the Mizuno (2006) model and the lower extremity in the Okamoto (2003) model. Regarding mechanical properties, since cadaveric data for paediatric subjects are sparse, research on the development of *in* *vivo* techniques to assess tissues properties or scaling methods is required. Within this aim of developing child models with better geometry and mechanical characteristics, two projects have been started a few years ago, the Digital Child Project and the Child Advanced Safety Project for European Roads as described in paragraph 3.2.

Validation of the models is a key point. Data on children are sparse. Scaling methods of adult corridors are useful however they are based on assumptions regarding the child responses. Data on child and adult volunteers in sled tests compared to adult cadaver responses in the same conditions can help to improve the scaling methods. This work has been initiated for frontal impact (Lopez-Valdez et al., 2010) and needs to be expanded to other crash configurations.

The published applications of the child and ATD models presented in this literature review focused on the evaluation of child restraint systems or injury mitigation systems. In most of these simulations, the child and ATD models were placed in an optimal position. However, studies have shown that real life presents a lot of misuse of the child restraint systems (Osvalder and Bohman, 2008) and a large variety of child postures (Van Rooij et al., 2005) that can lead to a decreased performance of the child restraint system. As a consequence, it would be interesting to use these models to investigate the effect of out of position in crash situations (Li et al., 2011, Kendall et al., 2009, Van Rooij et al., 2005).

Moreover, applications of these models in emergency manoeuvres like steering and braking have not been published. Only Kendall et al. (2009) proposed a parametric study where pre-impact braking was considered. Mainly crash events were studied in the literature, with a focus on the regulation sled tests performed at 48 or 50 km/h with acceleration levels above 21 g. However, it was highlighted in the introduction that pre-crash events at a low acceleration level around 1 g may significantly influence the position of the child in the child restraint system before a crash. Simulations that include the pre-crash event could be performed to evaluate the child restraint systems in situations closer to real traffic accident scenarios, if there was a child model valid for this loading scenario.

Muscular activity has not been considered in the currently available child and ATD models. However, in pre-crash events the muscle response is important to model because of its influence on the child kinematics and on the injury patterns of bony and ligamentous parts. Implementation of muscles in a child or ATD model would lead to a new numerical tool useful for both pre-crash and in-crash simulations.

As a conclusion, 18 child numerical models and 18 ATD numerical models are present in the literature. Finite element models are more likely to predict injuries and simulate contacts, whereas multi body models can reproduce kinematics in long duration pre-crash events. Improvements of geometry and mechanical characteristics are needed for all child models to improve the biofidelity in the low g loading environment. Numerical child and ATD models are valuable tools for parametric studies, for example to investigate different crash situations and evaluate child restraint systems for non-optimal sitting postures. If crash and pre-crash events are studied, modelling of muscular activity has to be considered in order to reproduce crash scenarios with more realistic boundary conditions. Data on child volunteers may be required to develop and validate such models.

4 CURRENT AND FUTURE WORK

The literature review of numerical child models is finished and reported in Chapter 3 of this report. A review paper is considered and may be submitted to a scientific journal by December 2012.

Currently, work is ongoing to evaluate the child and ATD multi body models in the MADYMO code, as described in 4.1. In parallel, finite element child and ATD models are collected and the availability of the models for use in this project is discussed with the respective organizations and individuals that have the models. Currently, only the Mizuno (2005) 3 year-old model is available. A decision will be taken in January 2013 on whether to proceed with the multi body models or change to finite element models. If the finite element approach is chosen, muscles will be implemented according to 4.2.

The next step will be to implement active muscle response in the chosen child model. To tune and validate this model, experimental data with muscle information on contractions are required. Therefore, a study of muscle activity with electromyography is planed with child volunteers, as describe in 4.3.

Lastly, the model will be applied to study how the child's muscle response can influence the outcome when children chose unstable sitting posture. This will provide a demonstrator of the improved child model capable of simulating muscle contractions.

A time plan from November 2012 until March 2014 is provided in chapter 5.

4.1 MULTI BODY MODELS

The MADYMO code will be used. The first step of this study is to compare the response of existing child and ATD multi body models to the volunteer data by Arbogast et al. (2009) and Stockman (2012). The following models will be included:

- MADYMO Child 6YO Facet
- MADYMO Child 10YO Facet
- MADYMO Q6
- MADYMO Hybrid III 6 YO
- Liu (2002) 6YO.

Based on the results, the most promising child or ATD model will be chosen to become an active model.

The second step will be to implement a representation of the musculature in the best candidate determined in the previous step. This will be done by adding controllers to the joints of the spine. Also, changing the joint mechanical properties may be required to improve the biofidelity of the model. Implementation of muscle contraction and the neural response will be based on the work proposed in the FFI project on active human body models (Östh et al., 2012). Tuning and validation of the model will be done by comparing the numerical results with experimental results, for example Arbogast et al. (2009) and Stockman (2012). If new data is generated in the project, according to 4.2, this will be included in the comparison.

Finally, the resulting model will be used in parametric studies to evaluate child restraint systems in pre-crash events.

4.2 Finite element muscle model

The muscle models actually implemented in the adult finite element model (Östh et al., 2012) are line muscles. They are basically springs without inertia properties, but when talking about car crashes, inertia has an important effect. Muscle mass and also muscle stiffness due to activation may affect the bones or ligaments responses. Muscle representation can be improved. The development of solid finite element muscles has already been done (Hedenstierna and Halldin, 2008). These muscles could be implemented in the whole body model of a child, taking the geometry and mechanical characteristics of child muscles into account.

4.3 Experimental studies

The experiments performed by Stockman et al. (2012) with child volunteers and ATDs in emergency manoeuvres illustrated that muscle activation may play an important role, in addition to the interaction between the child and the restraint system, on the resulting position of the child during emergency steering manoeuvres. If these manoeuvres would have been followed by a crash, the child occupants would probably have been injured. It is thus important to understand the kinematics of child occupants in such situations and to consider its active response with a child numerical model. During these experiments, only kinematic data were recorded and it is therefore interesting to complement this study with data on muscle contraction forces and activation for children. Muscle activity can be assessed for child volunteers using ElectroMyoGraphy (EMG) that measures the electrical potential in the muscle causing a muscle contraction.

The aim of this experiment will be to measure muscle activity in children of different ages and in unstable sitting postures, for example representing the child slipping out of the belt during in-board motion in steering manoeuvres. A simple sled test will be designed for this purpose. Muscles activity in the neck, back, lower and upper extremities will be measured and compared to the maximum voluntary contractions. The focus will be on activation level and reaction time of the selected muscles. This set of data can be used to tune the models.

In parallel, a new set of steering and braking manoeuvres are planned with new child restraint systems in the SAFER project *Småfolk*. The focus will be on 6 and 10 year-old children. Kinematics, anthropometry and belt geometries will be measured. The data will be available for this project. Therefore, the data will be processed to be suitable for validation of numerical models. Corridors, for instance of the head forward displacement, will be created and used for the model validation.

5 Time line

Table 4 illustrates the time line for the work until March 2014. Task 1, to evaluate the available multi body models as described in 4.1, will provide results for a decision in January 2013 if work will progress with either multi body models (task 2) or finite element models (tasks 3 and 4). Therefore, the timing of task 5, the demonstrator where the active child model is applied in a parameter study, varies. The two experimental activities described in 4.3 (tasks 6 and 7) are planned for the spring 2013. Three scientific publications are planned, the literature review and two papers on results from model evaluation and development of the active model. A final report will be delivered to Folksam in October 2013 and updated in March 2014, when the stipend ends.

Table 4: Time line until March 2014.

Tasks	2012	2013				2014
	Nov Dec	Jan Fev Mar	Apr May Jun	Jul Aug Sep	Oct Nov Dec	Jan Feb Mar
1. Evaluating the multi body models						
2. Implementing active muscle in multi body						
3. Evaluating finite element models						
4. Implementing active muscles in a finite element model						
5. Demonstrator						
6. Participating in experiments with braking and steering manoeuvres						
7. EMG study						
9. Scientific papers						
8. Final reports						

References

Andersson, M., Bohman, K., and Osvalder, A.-L. (2010). Effect of booster seat design on children's choice of seating positions during naturalistic riding. Ann Adv Automot Med, 54:171–180.

Andersson, M., Pipkorn, B., and Lövsund, P. (2012). Parameter study for child injury mitigation in near-side impacts through fe simulations. Traffic Inj Prev, 13(2):182–192.

Arbogast, K. B., Balasubramanian, S., Seacrist, T., Maltese, M. R., García-España, J. F., Hopely, T., Constans, E., Lopez-Valdes, F. J., Kent, R. W., Tanji, H., and Higuchi, K. (2009). Comparison of kinematic responses of the head and spine for children and adults in low-speed frontal sled tests. Stapp Car Crash J, 53:329–372.

Behr, M., Arnoux, P. J., Serre, T., Bidal, S., Kang, H. S., Thollon, L., Cavallero, C., Kayvantash, K., and Brunet, C. (2003). A human model for road safety: from geometrical acquisition to model validation with radioss. Comput Methods Biomech Biomed Engin, 6(4):263–273.

Bohman, K., Arbogast, K. B. and Bostrom, O. (2011). Head Injury Causation Scenarios for Belted, Rear-Seated Children in Frontal Impacts. Traffic Inj Prev, 12:62–70.

Bohman, K., Stockman, I., Jakobsson, L., Osvalder, A.-L., Bostrom, O., and Arbogast, K. B. (2011). Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers. Ann Adv Automot Med, 55:15–26.

Cao, L., Chen, H., Ren, X., and Ouyang, Z. (2010). Study on an integrated child safety seat. Applied Mechanics and Materials, 34-35:517–522.

Cui, Y., Yamaguchi, M., Mizuno, K., Tanaka, Y., and Yoshida, R. (2012). Fe analysis of child occupant kinematics in crs in side oblique impact. International Journal of Crashworthiness, 17:233–242.

Emam, A., Sennah, K., Howard, A., and Chapman, M. (2005). A study of injury parameters for rearward and forward facing 3-year-old child dummy using numerical simulation. International Journal of Crashworthiness, 10:211–222.

Final Rule, Federal Motor Vehicle Safety Standards 213, Child Restraint Systems, 49 CFR Part 571, Docket No. NHTSA–03–15351, Federal Register 68(121) (2003).

Forero Rueda, M. and Gilchrist, M. (2009). Comparative multibody dynamics analysis of falls from playground climbing frames. Forensic Science International, 191:52–57.

Haug, E., Choi, H.-Y., Robin, S and Beaugonin, M. (2004). Humna Models for Crash and Impact Simulation. Handbook of numerical anaylisis, 12:231-452.

Hedenstierna, S. and Halldin, P. (2008). How Does a Three-Dimensional Continuum Muscle Model Affect the Kinematics and Muscle Strains of a Finite Element Neck Model Compared to a Discrete Muscle Model in Rear-End, Frontal, and Lateral Impacts. Spine, 33:E236-45.

Hu, J., Klinich, K. D., Reed, M. P., Kokkolaras, M., and Rupp, J. D. (2012). Development and validation of a modified hybrid-iii six-year-old dummy model for simulating submarining in motor-vehicle crashes. Medical Engineering and Physics, 34:541–551.

Hu, J. and Mizuno, K. (2009). The kinematic behaviour and responses of hybrid iii 3yo dummy and child human fe model in isofix crs in frontal impact. International Journal of Crashworthiness, 14:391–404.

Iwamoto, M., Kisanuki, Y., Watanabe, I., Furusu, K., Miki, K., and Hasegawa, J. (2002) Development of a finite element model of the Total Human Model for Safety (THUMS) and application to injury reconstruction, Proceedings of the IRCOBI International Conference, 31–42.

Iwamoto, M., Omori, K., Kimpara, H., Nakahara, Y., Tamura, A., Watanabe, I., Miki, K., Hasagewa, J. and Oshita, F. (2003). Recent advances in THUMS: development of individual internal organs, brain, small female and pedestrian model. 4th European LS-DYNA Users Conference.

Johansson, M., Pipkorn, B., and Lövsund, P. (2009). Child safety in vehicles: validation of a mathematical model and development of restraint system design guidelines for 3-year-olds through mathematical simulations. Traffic Inj Prev, 10(5):467–478.

Kallieris, D., Barz, J., Schmidt, G., Heess, G., and Mattern, R. (1976). Comparison between child cadavers and child dummy by using child restraint systems in simulated collisions. In 20th Stapp Car Crash Conference, Dearborn, Michigan, USA, 1976. Society of Automotive Engineers.

Kapoor, T., Altenhof, W., Emam, A., and Howard, A. (2005). A comparison of the head and neck injury parameters on a tno p3 and a three-year-old hybrid iii child dummies from numerical simulations. SAE TECHNICAL PAPER SERIES, 2005-01-1303.

Kapoor, T., Altenhof, W., Tot, M., Howard, A., Rasico, J., Zhu, F., and Mizuno, K. (2008). Responses of the q3, hybrid iii and a three year old child finite element model under a simulated 213 test. SAE TECHNICAL PAPER SERIES, 2008-01-1121.

Kapoor, T., Altenhof, W., Howard, A., Snowdon, A., Rasico, J., Zhu, F., and Mizuno, K. (2010). Countermeasures to mitigate head and neck injuries to toddlers in frontal and lateral vehicle crash conditions. International Journal of Crashworthiness, 15:17–37.

Kendall, R., Sherwood, C., and Crandall, J. (2009). A computational study of rear-facing and forward-facing child restraints. SAE International Journal of Passenger Cars- Mechanical Systems, 1:938–970.

Koizumi, T., Tsujiuchi, N., and Uchida, Y. (2005). Impact injury rating of child fe human model for 3-year-old. In IMAC-XXIII: Conference and Exposition on Structural Dynamics.

Koplin Winston, F., Arbogast, K. B., Lee, L. A., and Menon, R. A. (2000). Computer crash simulations in the development of child occupant safety policies. Arch Pediatr Adolesc Med, 154(3):276–280.

Lopez-Valdes, F. J., Seacrist, T., Balasubramanian, S., Maltese, M. R., Arbogast, K. B., Tanji, H., Higuchi, K. and Kent, R. (2010). A Methodology to Obtain Kinematic Corridors for Pediatric Occupants in Frontal Impacts. WCB 2010, IFMBE Proceedings 31, 529–532,

Li, Z., Zhang, W., Kapoor, T., and Altenhof, W. (2011). Crash analysis of a three-year-old human child model in side impacts considering normal and incorrect crs usage. International Journal of Crashworthiness, 16:457–467.

Liu, X. J. and Yang, J. K. (2002). Development of child pedestrian mathematical models and evaluation with accident reconstruction. Traffic Injury Prevention, 3:321–329.

MADYMO Human Models Manual Release 7.4.1; 2012.

MADYMO Model Manual Release 7.4.1; 2012.

Meijer, R., Rodarius, C., Adamec, J., Van Nunen, E., and Van Rooij, L. (2008). A first step in computer modelling of the active human response in a far-side impact. International Journal of Crashworthiness, 13:643–652.

Mendoza-Vazquez, M. (2012). Rib and Thoracic Response in Frontal Car Crashes: A Study Using a Finite Element Human Body Model. Licentiate thesis, Institutionen för tillämpad mekanik, Fordonssäkerhet, Chalmers tekniska högskola.

Menon, R., Ghati, Y., and Jain, P. (2007). Madymo simulation study to optimize the seating angles and belt positioning of high back booster seats. In The 20th International Technical Conference on the Enhanced Safety of Vehicles Conference.

Mertz, H.J., Irwin, A.L., Melvin, J.W., Stalnaker, R.L. and Beebe, M.S. (1989). Size, weight and biomechanical impact response requirements for adult size small female and large male dummies, SAE International Congress, SAE Paper 890756.

Mizuno, K., Iwata, K., Deguchi, T., Ikami, T., and Kubota, M. (2005). Development of a three-year-old child fe model. Traffic Inj Prev, 6(4):361–371.

Mizuno, K., Iwata, K., Namikiri, T., and Tanaka, N. (2006). Comparison of human fe model and crash dummy responses in various child restraint systems. International Crashworthiness Conference, Athens, Greece.

Okamoto, M., Takahashi, Y., Hitosugi, M., Mori, F., Hitosugi, M., Madeley, J., Ivarsson, J., and Crandall, J. R. (2003). Development of finite element model for child pedestrian protection. In The 18th International Technical Conference on the Enhanced Safety of Vehicles.

Östh, J., Brolin, K., Carlsson, S., Wismans, J., and Davidsson, J. (2012a). The occupant response to autonomous braking: a modeling approach that accounts for active musculature. Traffic Inj Prev, 13(3):265–277.

Osvalder, A.-L. and Bohman, K. (2008). Misuse of booster cushions - an observation study of children's performance during buckling up. Ann Adv Automot Med, 52:49–58.

Ouyang, J.; Zhu, Q.; Zhao, W.; Xu, Y.; Chen, W. and Zhong, S. (2005) Biomechanical assessment of the pediatric cervical spine under bending and tensile loading. Spine, 30:E716-E723

Pediatric Injury Biomechanics: Archive and Textbook. (2013). Springer New York.

Sasaki, Y., Yamaguchi, M., and Mizuno, K. (2009). Basic parameters affecting child occupant responses in side impact. International Journal of Vehicle Safety, 4:300–314.

Seacrist, T., Balasubramanian, S., García-España, J. F., Maltese, M. R., Arbogast, K. B., Lopez-Valdes, F. J., Kent, R. W., Tanji, H., and Higuchi, K. (2010). Kinematic comparison of pediatric human volunteers and the hybrid iii 6-year-old anthropomorphic test device. Ann Adv Automot Med, 54:97–108.

Sherwood, C. P., Shaw, C. G., Van Rooij, L., Kent, R. W., Crandall, J. R., Orzechowski, K. M., Eichelberger, M. R., and Kallieris, D. (2003). Prediction of cervical spine injury risk for the 6-year-old child in frontal crashes. Traffic Inj Prev, 4(3):206–213.

Stockman, I., Bohman, K., Jakobsson, L., Brolin, K. (2012). Kinematics of child volunteers and child anthropomorphic test devices during emergency braking events in real crash environment. Traffic Inj Prev, In press.

Stockman, I. (2012). Child Passenger Kinematics in Emergency Manoeuvres. Licentiate thesis, Institutionen för tillämpad mekanik, Fordonssäkerhet, Chalmers tekniska högskola.

Surcel, M.-D. and Gou, M. (2005). Development of a mathematical model for evaluating child occupant behaviour in the case of a vehicle side impact simulation. International Journal of Crashworthiness, 10:111–118.

Thunnissen, J.G.M., Happee, R., Eummelen, P. and Beusenberg, M.C. (1994), Scaling of adult to Child Responses applied to the thorax, IRCOBI Conference, Lyon, September 21-23, 1994.

Toyota Motor Corporation, Toyota Central Labs Inc. (2008). Users' Guide of Computational Human Model THUMS® – AM50 Occupant Model: Version 3.0–080225

Tropiano, P., Thollon, L., Arnoux, P. J., Huang, R. C., Kayvantash, K., Poitout, D. G., and Brunet, C. (2004). Using a finite element model to evaluate human injuries application to the humos model in whiplash situation. Spine (Phila Pa 1976), 29(16):1709–1716.

Turchi, R., Altenhof, W., Kapoor, T. and Howard, A. (2004). An investigation into the head and neck injury potential of three-year-old children in forward and rearward facing child safety seats. International Journal of Crashworthiness, 9:4, 419-431

Untaroiu, C. D., Crandall, J. R., Takahashi, Y., Okamoto, M., Ito, O., and Fredriksson, R. (2010). Analysis of running child pedestrians impacted by a vehicle using rigid-body models and optimization techniques. Safety Science, 48:259–267.

Van Hoof, J., De Lange, R. and Wismans, J. (2003). Improving Pedestrian Safety Using Numerical Human Models. Stapp Car Crash journal. 47:401-436. SAE Report No. 2003-22-0018.

Van Rooij, L., Meissner, M., Bhalla, K., Crandall, J., Longhitano, D., Takahashi, Y., Dokko, Y., and Kikuchi, Y. (2004). A comparative evaluation of pedestrian kinematics and injury prediction for adults and children upon impact with a passenger car. SAE TECHNICAL PAPER SERIES, 2004-01-1606.

Van Rooij, L., Harkema, C., de Lange, R., de Jager, K., Bosch-Rekveldt, M., and Mooi, H. (2005). Child poses in child restraint systems related to injury potential: Investigations by virtual testing. In The 19th International Technical Conference on the Enhanced Safety of Vehicles.

Vezin, P., Bruyère, K. and Bermond, F. (2001). Comparison of head and thorax cadaver and hybrid iii responses to a frontal sled deceleration for the validation of a car occupant mathematical model. In The 17th International Technical Conference on the Enhanced Safety of Vehicles.

World Health Organization, Global status report on road safety: time for action. Geneva, 2009.

Young, J.W., Reynolds, H.M., McConville, J.T., Snyder, R.G. and Chandler, R.F. (1976) Development and evaluation of masterbody forms for 3- and 6-year-old-child dummies, FAA-AM-76-9, UMTRI.

Zhang, W., Kapoor, T., Tot, M., Altenhof, W., Howard, A., and Mizuno, K. (2007). A comparison of the kinematics of a child finite element model and the hybrid iii 3-year-old dummies in frontal crashes. SAE TECHNICAL PAPER SERIES, 2007-01-0977.

Zhang, W., Kapoor, T., Altenhof, W., Howard, A., and Mizuno, K. (2009). Implementation of child biomechanical neck behaviour into a child fe model. SAE TECHNICAL PAPER SERIES, 2009-01-0472.

Zhao, A., Hong, S.-W., Park, C.-K., Kan, C. D., Park, S. H., and Bae, H. (2009). Child safety analysis for forward-facing child restraint system in frontal impact. International Journal of Crashworthiness, 14:151–163.

CASPER project: www.casper-project.eu

Digital Child Project: www.uab.edu/scib/

Dynamore: www.dynamore.de - www.dynamore.de/en/products/models/child

Humanetics: www.humaneticsatd.com

Appendix A: project description in the application

The overall aim of the proposed project is to increase safety of child car occupants and thereby reduce the number of traffic induced injuries to children ages 3 through 12. Specifically, this will be done by creating computer models of children that include active musculature and that can complement ongoing research with volunteer data. The aim with the active child Human Body Model (HBM) is to simulate pre-crash events with biofidelic response at load levels and in maneuvers that cannot be performed with volunteer children. The child HBM can also be used to understand the protective principles of forward facing children, how they interact with current and future car restraints.

HBM are valuable tools to simulate the pre-crash and in-crash occupant response in order to develop advanced restraint systems and reconstructions of real life crashes. This project will focus on developing and improving child HBM that are capable of tensing musculature to simulate bracing. This is essential to simulate occupant kinematics in pre-crash. Such child HBM can complement the ongoing experimental research, with child volunteers, to study the child response and restraint interaction in pre-crash events with higher g-loading. Understanding the biomechanics of children in pre-crash is vital to improve child safety. Accident research by Bohman et al. (2011) has shown that accidents where children sustain head injuries include oblique impact directions and/or pre-crash maneuvers. In pre-crash events or maneuvers the child occupants interact with the car restrains, such as seat belts and booster seats. To increase child safety it is necessary to understand the biomechanics of children. At these low energy levels, the muscle tension has an important influence on the kinematics of the children. In volunteer studies (Bohman et al. 2011) with children in pre crash steering, it is apparent that the older children tense their shoulder muscles differently from younger children and therefore have a better interaction with the shoulder belt and no slip out. Muscle and muscle memory matures in children and therefore it may not be possible to apply muscle modeling techniques for adults to the children.

This project will include fundamental research on how to simulate the active muscle response in a biofidelic manner. It will complement ongoing research that is implementing closed loop control to simulate the active muscle response of adults in pre and in-crash scenarios (Östh 2011, Östh et al. 20112010, Östh and Brolin 2010). It will consider human body models of children of different ages to find control parameters and muscle recruitment strategies that fit each age group. Literature will be scanned for experimental studies that are need to complement the numerical and programming work, to find material parameters and validation data. If necessary, new volunteer studies will be performed. The overall aim is to have multi body or finite element models of children from ages 3 through 12 with active muscle responses.

The proposed project will strengthen the competence platform on human body modeling within SAFER/Chalmers toward child safety and bring the two clusters of human body modeling and child safety closer. Specifically, this project will be executed in close collaboration with the two Ph.D. students and researchers in the project on active muscle modeling for adults (see Other funding above) that focus on simulation pre-crash braking and lane-change maneuvers with finite element human body models. At the Division of Vehicle Safety, the main applicant and 7 PhD students are now active with projects that include human body modeling. The suggested post-doc will strengthen the senior side of this cluster, in addition to coming to an active research area.

References in support of methodology

Östh, J. Active Muscle Responses in a Finite Element Human Body Model, Licentiatavhandling, Chalmers University of Technology, 2010.

Östh J, Brolin K, Happee R. Active muscle response using feedback control of a finite element human arm model. Comput Methods Biomech Biomed Engin. Jan 1:1 [Epub ahead of print], 2011.

Östh J, Brolin K, Wismans J. Implementing Active Properties of Musculature to Obtain Posture Maintaining Human Body Models for Crash Simulations. 6th World Congress of Biomechanics, Singapore, August 1-6. 2010.

Östh J, Brolin K. Closed loop control of FE arm model. IV European Conference on Computational Mechanics, Paris, France, May 16-21. 2010.

Bohman K, Arbogast K, Boström O. "Head Injury Causation Scenarios for Belted, Rear-Seated Children in Frontal Impact". Traffic Injury Prevention, 12:62-70, 2011

Bohman K, Stockman I, Jakobsson L, Osvalder A-L, Boström O, Arbogast KB. "Kinematics and Shoulder Belt Position of Child Rear Seat Passengers during Vehicle Maneuvers". The 55th AAAM Annual Conference, Annals of Advances in Automotive Medicine, 2011

Jakobsson L, Bohman K, Andersson M, Stockman I, Boström O, Svensson M, Svanberg H, Wimmerstedt M, Arbogast KB. Rear Seat Safety in Frontal to Side Impacts – Focusing on Occupants from 3yrs to Small Adults. ESV paper no. 11-0257, Washington DC, 2011