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Safety of children in cars: A review of biomechanical aspects and human body models

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ABSTRACT

The protection of children in motor vehicle crashes has improved since the introduction of child restraint systems. However, motor vehicle crashes remain one of the top leading causes of death for children. Today, computer-aided engineering is an essential part of vehicle development and it is anticipated that safety assessments will increasingly rely on simulations. Therefore, this study presents a review of important biomechanical aspects for the safety of children in cars, including child human body models, for scenarios ranging from on-road driving, emergency maneuvers, and pre-crash events to crash loading. The review is divided into four parts: Crash safety, On-road driving for forward facing children, Numerical whole body models, and Discussion and future outlook.

The first two parts provide ample references and a state-of-the-art description of important biomechanical aspects for the safety of children in cars. That children are not small adults has been known for decades and has been considered during the development of current restraints that protect the child in the crash phase. The head, neck, thorax, and pelvis are body areas where development with age changes the biomechanics and the interaction with restraint systems. The rear facing child seat distributes the crash load over a large area of the body and has proved to be a very efficient means of reducing child injuries and fatalities. Children up to age 4 years need to be seated rearward facing for optimal protection, mainly because of the proportionally large head, neck anthropometry and cartilaginous pelvis. Children aged 4 up to 12 years should use a belt positioning booster together with the vehicle seat belt to ensure good protection, as the pelvis is not fully developed and because of the smaller size of these children compared to adults. On-road driving studies have illustrated that children frequently change seated posture and may choose slouched positions that are poor for lap belt interaction if seated directly on the rear seat. Emergency maneuvers with volunteers illustrate that pre-crash loading forces forward-facing children into involuntary postures with large head displacements, having potential influence on the risk of head impact. Children, similar to adults, benefit from the safety systems offered in the vehicle. By providing child adaptability of the vehicle, such as integrated booster cushions, the child-restraint interaction can be further optimized. An example of this is the significant reduction of lap belt misuse when using integrated boosters, due to the simplified and natural positioning of the lap belt in close contact with the pelvis. The research presented in this review illustrates that there is a need for enhanced tools, such as child human body models, to take into account the requirements of children of different ages and sizes in the development of countermeasures.

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To study how children interact with restraints during on-road driving and during pre- and in-crash events, numerical child models implementing age-specific anthropometric features will be essential. The review of human whole body models covers multi body models (age 1.5 to 15 years) and finite element models (ages 3, 6, and 10 years). All reviewed child models are developed for crash scenarios. The only finite element models to implement age dependent anthropometry details for the spine and pelvis were a 3 year-old model and an upcoming 10 year-old model. One ongoing project is implementing active muscles response in a 6 year-old multi body model to study pre-crash scenarios. These active models are suitable for the next important step in providing the automotive industry with adequate tools for development and assessment of future restraint systems in the full sequence of events from pre- to in-crash.

Contents

1. Introduction

The protection of children in motor vehicle crashes has improved since the introduction of child restraint systems. However, car crashes are the second leading cause of death for children between 5 and 14 years old [1]. Different parts of the world face different challenges with regards to protecting children in traffic. In countries like India and China, child pedestrians face considerable risks of injury and fatality, and child car occupants are rarely protected with restraints developed specifically for children. In, for example, North America, Australia, and Europe, child restraints are mandatory for child occupants and still 32% of European road traffic fatalities for children up to 14 years of age involved car occupants [2]. Hence there is a need to continue research, education and policy activities to enhance the safety of children in all parts of our world.

Child occupant fatalities and injuries occur mostly in frontal and side impacts for children seated in passenger vehicles. The head is the most frequently injured body region for forward-facing children regardless of crash direction [3–5]. To understand how children are injured, Bohman et al. [6] studied the causation scenarios of head injuries in frontal impacts for rear-seated, forward-facing, restrained children and 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 maneuvers such as braking, steering or a combination of both, influenced the kinematics of children before the impact and affected the child's interaction with the restraint systems. Consequently, to reduce head injuries further, child protection and restraint systems need to be evaluated for the whole crash sequence, including the pre-crash phase and how the child interacts with restraints in everyday on-road driving. This example illustrates the necessity to have a thorough understanding of the biomechanics of children in a range of loading situations from gravity to high severity crash loading in order to improve the safety for children today. Children are not small adults [7] and especially the head, spine, thorax, and pelvis have implications for vehicle safety. Among others, a textbook [8] from 2013 describes thoroughly pediatric biomechanics in crash loading while Stockman [9] focuses on emergency events. To the best knowledge of the authors there are no publications reviewing child kinematics for the range of scenarios from on-road driving, emergency maneuvers, pre-crash events, and through to crash loading.

Traditionally, Anthropomorphic Test Devices (ATDs) are used to evaluate safety systems in crash loading. Four main child sized ATD series are available: the Hybrid III, CRABI, the P and 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 [10] with anthropometry data collected in the US, Europe and Japan, was used. However, in recent year numerical Human Body Models (HBMs) are becoming increasingly popular and are used to simulate both pre-crash and in-crash occupant responses. As computer capacity is increasing, safety development and assessment of vehicles are relying more and more on simulation tools. The HBMs have the potential advantage over ATDs to simulate anatomical details and predict biofidelic kinematics and injuries at tissue level. HBMs are either Finite Element (FE) or Multi Body (MB) models. FE models are usually models with detailed geometry intended for crash simulations and have strong contact definitions which are of importance to model the interaction between the occupant and the restraint systems. MB models usually have fast computational times and are relatively simple and easy to use, but contact definition is complex, and the output is mainly kinematic. While most ATDs are developed for impacts in one direction, and are therefore limited to either frontal, lateral or rear impacts, detailed HBMs can represent the human response to omnidirectional impacts if sufficiently validated. In addition, there are adult models intended for low g-loading that implement the active muscle response [11]. Hence, biofidelic child HBMs can enable optimization of safety systems based on real world data and can increase the understanding of child specific injury mechanisms. However, such models need thorough validation and should capture age-specific anatomical changes. Whole body models of children are rare and have many limitations. Still, they are important for future research and much research is currently ongoing. Therefore, an up to date overview of published whole body child HBMs would be beneficial.

This aim of this paper is to present a review of important biomechanical aspects for the safety of children in cars, including child HBMs, with a focus on the head, spine, thorax, and pelvis. The review is divided into four parts: Crash safety, On-road driving, Numerical whole body models, and Discussion and future outlook.

2. Crash safety

It is known that children are not small adults. Already in 1969, Burdi et al. [7] published a study on the structural differences between