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# A finite element model of a six-year-old child for simulating pedestrian accidents

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ABSTRACT

Child pedestrian protection deserves more attention in vehicle safety design since they are the most vulnerable road users who face the highest mortality rate. Pediatric Finite Element (FE) models could be used to simulate and understand the pedestrian injury mechanisms during crashes in order to mitigate them. Thus, the objective of the study was to develop a computationally efficient (simplified) six-year-old (6YO-PS) pedestrian FE model and validate it based on the latest published pediatric data. The 6YO-PS FE model was developed by morphing the existing GHBMC adult pedestrian model. Retrospective scan data were used to locally adjust the geometry as needed for accuracy. Component test simulations focused only the lower extremities and pelvis, which are the first body regions impacted during pedestrian accidents. Three-point bending test simulations were performed on the femur and tibia with adult material properties and then updated using child material properties. Pelvis impact and knee bending tests were also simulated. Finally, a series of pediatric Car-to-Pedestrian Collision (CPC) were simulated with pre-impact velocities ranging from 20 km/h up to 60 km/h. The bone models assigned pediatric material properties showed lower stiffness and a good match in terms of fracture force to the test data (less than 6% error). The pelvis impact force predicted by the child model showed a similar trend with test data. The whole pedestrian model was stable during CPC simulations and predicted common pedestrian injuries. Overall, the 6YO-PS FE model developed in this study showed good biofidelity at component level (lower extremity and pelvis) and stability in CPC simulations. While more validations would improve it, the current model could be used to investigate the lower limb injury mechanisms and in the prediction of the impact parameters as specified in regulatory testing protocols.

## 1. Introduction

Approximately 1.25 million people die each year as a result of road traffic crashes worldwide, and 20 to 50 million more people suffer non-fatal injuries (WHO, 2015). According to the National Highway Traffic Safety Association (NHTSA), 4735 pedestrians (14% of total fatalities) were killed in the United States in 2013 by traffic collisions (NHTSA, 2015). Meanwhile, 21% of children under 14-year-old that were killed in traffic crashes were pedestrians. The head and lower extremities are the most common regions of injury and deserve specific protection research (Ivarsson et al., 2006).

While methodologies for studying pedestrian protection do exist, each has limitations. Several sub-system tests (head, upper and lower legs) were developed for pedestrian protection in Asia (Ishikawa et al., 2003) and Europe (Euro NCAP, 2015). However, only a headform impact test relates to child pedestrian protection (Euro NCAP, 2015). Testing with anthropometric test devices (ATD)/dummies is also a conventional methodology to research kinematics and injury assessment. However, only an adult full-body dummy (Polar dummy) has been developed and validated against PMHS tests for pedestrians (Fredriksson et al., 2011a; Shin et al., 2006; Untaroiu et al., 2010a, 2010b). Due to differences in impact location and material properties, existing subsystem tests and dummies designed for adult pedestrian cannot be used for child pedestrian protection by simple scaling (Cappetti et al., 2008; Moradi and Lankarani, 2011; Untaroiu et al., 2008). A few child Finite Element (FE) models have been developed and employed

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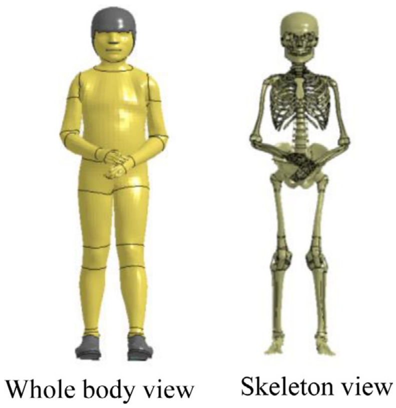

**Fig. 1.** The 6YO-PS FE model.

in numerical simulations of car-to-pedestrian collisions (CPC) (Lv et al., 2016; Mao et al., 2014; Okamoto et al., 2003). However, existing FE models have inherent limitations at the development and validation levels. A pedestrian FE model was constructed using the MRI scans from a six-year-old child, but the material properties still need to be improved (Ito et al., 2007; Okamoto et al., 2003). A ten-year-old pedestrian model was developed and validation simulations were performed (Zhu et al., 2016). However, this child model has significant anthropometric differences to a six-year-old child, so its responses cannot be simply scaled to 6YO. While the development of a 6-year-old pedestrian model (Lv et al., 2016) was recently reported, the validation of its lower extremity region, the most injured body region, was not reported yet. In addition, all previous child models lack the benefit from the material and component test data that has been published recently.

In this paper, the development and validation of the 6YO-PS FE model is presented. The model mesh was scaled and then morphed from a current adult model to an average child's geometry, and its biofidelity was verified at lower extremity and pelvis level against PMHS test data. Finally, the model capability to predict pedestrian lower extremity injuries was verified in CPC simulations.

## 2. Methods

### 2.1. Development of six-year old child model

The child model (6YO) was developed based on an existing adult model corresponding to a 5th percentile female anthropometry (Fig. 1). First, the adult model was linearly scaled to an average six-year-old child's overall anthropometry taken from literature (Synder et al., 1977). Then, radial basis function interpolation with a thin-plate spline as the basis function (RBF-TPS) was used with a relaxation algorithm to morph from the scaled model to the final target geometry of the 6YO FE model. The morphing method is detailed in the literature (Vavalle et al., 2014) and is briefly reviewed here.

To initiate the morphing process, a set of homologos landmarks on a target and reference geometry are required. The reference surface represents the baseline finite element mesh and thus the first step in this process was to convert the surface of the linearly scaled FE mesh to a polynomial CAD surface using standard software (Geomagic Studio, 3D Systems, Cary NC). The target surface was an altered version of a 6YO seated CAD surface from a statistical model developed by Reed et al. (2001). The two surfaces were brought into the same coordinate system and homologous landmarks were created. Homologous landmarks in the same coordinate system were made using ANTS software, which is further described in the literature (Avants and Gee, 2004; Avants et al., 2008; Bookstein, 1997, 1989; Donato and Belongie, 2002; Vavalle et al., 2014). Homologous landmarks are evenly spread across the surfaces used and are at the same relative location on each surface.

The RBF-TPS method calculates thin-plate spline coefficients from landmark locations on reference and target geometries, and then applies the spline equations to the reference mesh to create the target mesh. The result is a morphed target mesh which is based on the reference. An advantage of this method is that it allows for the description of the target geometry, 6YO in this case, with a surface-only set of landmark points.

After the morphing process, anthropometry was compared to gross values in the literature to verify the accuracy of the morph. Retrospective scan data were used to locally adjust the geometry as needed for accuracy, e.g. in the C-spine. The initial morphed model (Untaroiu et al., 2015) was found to underestimate the target mass of 23.4 kg. Therefore, a second morphing process was performed to achieve a more anthropometrically accurate body shape, using data from the recent statistical geometry in a standing posture (Park and Reed, 2015).

Once again the same RBF-TPS method as described above was used with 8000 homologous surface landmarks. The implemented morphing method generated a quality mesh with over 98% of the elements passing targets set by the GHBMC prior to post-morph mesh adjustments (Table 2). The elements below quality thresholds were edited manually to achieve agreement with GHBMC program targets.

### 2.2. Model validation

#### 2.2.1. Validation at component level

In testing (Ouyang et al., 2003b), long bones of lower extremities (femurs and tibias) were extracted from two 6YO PMHS. Both the distal and proximal ends of long bones were potted in cups. Then, an impactor driven by a universe machine (SWD-10) loaded long bones at the middle-shaft location until failure under quasi-static three-point AP bending (Ouyang et al., 2003b). These tests were simulated in LS-DYNA software (LSTC, Livermore, CA) under simplified conditions (Fig. 2) due to limited published test information. The FE models of the impactor, cup supports and ground were defined as rigid bodies. Nodes on both bones' ends were rigidly attached to the cup supports, which were supported by the fixed ground. An impactor loaded the long bone at its middle location constantly with the same velocity (0.5 m/min) as in testing.

Initially, the material properties of a male 50th percentile model (M50) (Yue et al., 2011; Shin et al., 2012; Untaroiu et al., 2013; Yue and Untaroiu, 2014) were assigned to the child model. However, because a higher bending stiffness and femoral failure force were predicted in FE simulations, the value of Young's modulus for the child femoral cortical bone was set as 9 GPa based on a published Young's modulus vs. age curve (Currey and Butler, 1975; Ivarsson et al., 2004). Since no published data regarding yield stress of a child femur was identified in the literature, the yield stress was assumed to be proportional to the Young's modulus and was calculated as 70.8 MPa. The failure strain was assumed to be the same as an adult's femur cortical bone (0.8%) since no data showing it changes with age was identified in literature. Similarly, due to the lack of pediatric PMHS test data, the Young's modulus of child tibia cortical bone was obtained by scaling adult data, assuming the same age variation as in femoral material properties. Therefore, the Young's modulus of six-year-old child tibia cortical bone was considered as 11.67 GPa and the yield stress and failure plastic strain were assumed as the same as child femoral properties (Table 1).

Ligament failure caused by lateral bending is a common knee injury for pedestrians during CPC accidents. Four-point bending tests were performed using adult PMHS specimens to estimate knee tolerance under valgus bending loading (Bose et al., 2008). Iso-