

Response Surface Generation for Kinematics and Injury Prediction in Pedestrian Impact Simulations

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ABSTRACT

This study concerns the generation of response surfaces for kinematics and injury prediction in pedestrian impact simulations using human body model. A 1000-case DOE (Design of Experiments) study with a Latin Hypercube sampling scheme is conducted using a finite element pedestrian human body model and a simplified parametric vehicle front-end model. The Kriging method is taken as the approach to construct global approximations to system behavior based on results calculated at various points in the design space. Using the response surface models, human lower limb kinematics and injuries, including impact posture, lateral bending angle, ligament elongation and bone fractures, can be quickly assessed when either the structural dimensions or the structural behavior of the vehicle front-end design change. This will aid in vehicle front-end design to enhance protection of pedestrian lower limbs.

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INTRODUCTION

Pedestrian protection has been drawing attention for more than two decades. In 2008, pedestrian fatalities made up 12%-33% of all road fatalities in the US, European Union, and Japan [1]. Statistics show that the lower limb is the most frequently injured body part in car-to-pedestrian accidents [2], and that more than 30% of all pedestrians involved in car-to-pedestrian accidents suffer knee injuries [3].

In impacts with the vehicle front-end, pedestrian lower limbs will contact with the bumper system first, which will create a turning moment about the center of gravity of the pedestrian and cause the upper body to arc downwards. The upper leg, pelvis, chest and head will contact with the bonnet leading edge, bonnet and windshield successively [4], as shown in Figure 1.

In regulatory tests, legform impactors are used to evaluate lower limb injuries of pedestrians when laterally impacted by a vehicle. Popular legform impactors include the EEVC pedestrian legform impactor (EEVC-PLI) and the Flex legforms [5, 7, 6]. Due to the repeatability and reusability requirement for testing, simplified structures are usually preferred in the design of the impactors. They are usually unable to completely reflect real lower limb injury

mechanisms and kinematics due to their design limitations [7-8].



Figure 1. Kinematics of pedestrian impacts with vehicle front-end [9].

In order to enhance the real-life protection of pedestrians, a validated finite element full-body pedestrian human body model (HBM) is used as an effective tool for the study of lower limb injuries. It can provide realistic kinematic lower limb response in real-world accidents and can be used to assess pedestrian injuries at the bone and tissue level.

To evaluate the vehicle protection performance, it is necessary to give a quick prediction on human body kinematics and injury levels under different impact loading conditions. Response surface (RS) methodology is taken as the approach to construct global approximations to system behavior based on results calculated at various points in the design space [10]. It explores the relationships between input design variables and one or more responses [11]. The main ideal is to use a sequence of design experiments to obtain the

response of a new design. Global approximations are often utilized in multidisciplinary optimization [12] or in reliability calculations [13]. Response surface modeling approaches are widely used in aerospace engineering [14], structural design [15], and mechanical engineering [16].

To deal with the highly nonlinear responses in car-pedestrian impacts, Kriging models are used since they can give global approximations with relatively good accuracy [17-18]. In recent years, the Kriging method has found wider application as a spatial prediction method in engineering design. Design of experiment (data sampling) plays an important role, especially when building Kriging models [19]. Latin Hypercube sampling, or other space filling methods, are typically used as the data sampling strategy in combination with the Kriging method [20-21].

This paper documents the generation of response surfaces for kinematics and injury prediction in pedestrian impact simulations using human body model. A computationally efficient, parametric vehicle model with adjustable geometric and stiffness variables to represent different vehicle front end configurations has been developed. This model has been validated by performing impact simulations with a human body model in a standing posture and comparing to similar simulations with a detailed finite element model of a vehicle front structure. Impact simulations between simplified vehicle models with different stiffness or geometry design variable values and a standing finite element human body model have been performed.

Several response surfaces for pedestrian human lower limb kinematics and injury predictions are generated using the numerical DOE (Design of Experiments) study. The accuracy of the RS models is validated with additional check points which are not in the DOE matrix. Using the RS models, human lower limb injuries, including ligament elongation and bone fractures, can be quickly assessed when either the structural dimensions or the structural behavior of the vehicle front-end design changes. This will aid in vehicle front-end design to enhance pedestrian protection of lower limbs.

MODEL SETUP

To assess the protection performance of various vehicle front-end designs, simulations of the finite element human body model in a standing posture impacted by the simplified vehicle model with different design variable values were carried out (Figure 2). The impact speed of the vehicle was 40 kpm, and the pedestrian was struck laterally, at the centerline of the vehicle. The trailing lower limb on the right side was the first contact with the vehicle.

Human Body Model (HBM)

The full-body mid-size pedestrian model (HBM) in this paper was first developed by General Motors (GM) and the University of Virginia (UVA) in 2007 (Figure 2) [22]. The model is 177 cm high and weighs 77 kg, which represents a

50th percentile male pedestrian in a standing posture. It is an LS-DYNA based finite element model, containing about 370 parts and 130,000 elements, including 83,900 solid elements and 45,000 shell elements. It consists of FE lower limb models, rigid foot and shoe models, a rigid pelvis, a FE pelvic flesh model and other upper body part models. The biofidelity of the lower limbs has been validated at component level [23, 24, 25]. The kinematics of the HBM has been validated at full-scale level, using the data from 7 full-scale Post Mortem Human Subjects (PMHS) impact tests [26]. The HBM can therefore be used to evaluate the injuries and kinematics of human lower limbs under different impact loading conditions more realistically.

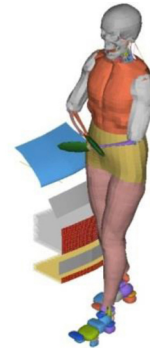


Figure 2. FE modeling of HBM impacts with simplified vehicle front-end model.

Kinematics Description

Kinematics of the first-struck right lower limb is assessed using five markers; their locations are shown in Figure 3. Time histories of the corresponding nodal coordinates in the global coordinate system are output to give their spatial position during impact. This could provide reference points for drawing the lower limb posture at a specified moment, e.g. the right lower limb posture at maximum bending angle.

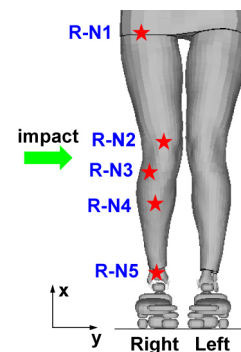


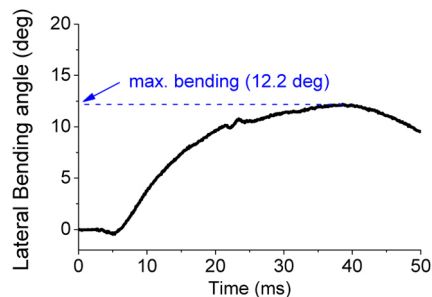
Figure 3. Kinematics markers on the right lower limb.

Considering the typical lateral impact situation for pedestrians, the lateral bending angle is taken as an important output parameter. A knee joint coordinate system was defined in order to describe the three rotational motions of the knee joint [27], with the lateral bending angle taken as global

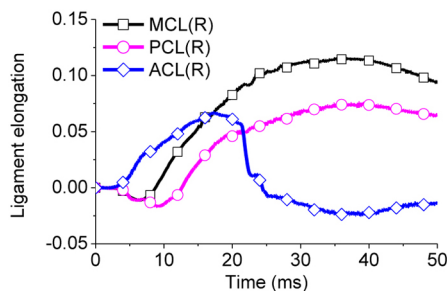
kinematic parameter that predicts the risk of knee ligament injury.

Injury Parameter Definition

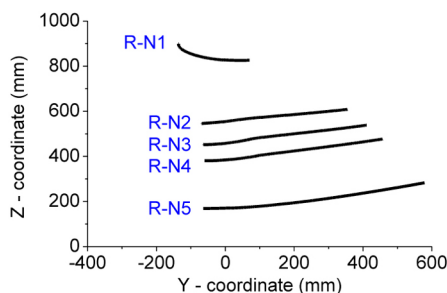
Ligament rupture and bone fracture are the most common injury patterns in the lower limb [2, 28]. To evaluate the human body injuries, several parameters are output in the HBM simulations. The ligament elongation, defined as the ratio of the change in length to the original ligament length, is taken to predict ligament injury in the HBM. It is calculated from columns of nodes selected along the length of each of the four knee joint ligaments. It has been found that fracture of the femur and/or tibia shaft usually results from acceleration of the lower limb during contact with the vehicle [29]. Therefore, maximum accelerations measured at tibia are also output. Maximum bending moments at possible bone fracture locations are also recorded, and will be used to evaluate bone fracture risk. Typical impact responses of the HBM impacted with one detailed vehicle model are shown in Figure 4 [30].



(a). Lateral bending angle (right lower limb)



(b). Knee ligament elongation (right lower limb)



(c). Trajectory of the kinematics markers (right lower limb)

Figure 4. Typical time histories of the HBM response in impact with vehicle front-end.

Parametric Vehicle Front-End Model

The simplified parametric vehicle model used in the DOE study is shown in Figure 5. It consists of five parts, representing the front faces of the bonnet leading edge (BLE) (Part 1), upper grill (Part 2), main bumper (Part 3), lower grill (Part 4) and spoiler (Part 5). Five geometry variables and seven stiffness variables are included.

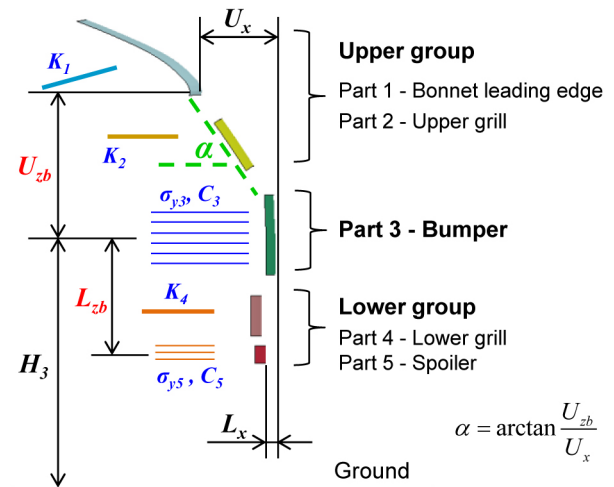


Figure 5. The simplified parametric vehicle model for DOE and RS generation [30].

To reflect the local deformation on the vehicle in pedestrian-vehicle impact, Part 3 and Part 5 are modeled by deformable shell elements to provide a deformable contact surface. An array of uniformly distributed beam elements are used to model the dynamic stiffness of the bumper and spoiler structures. When impacting with pedestrian legs, such a structure can have a more realistic response in terms of different contact time and contact location of the two lower limbs. Proper ranges of the upper and lower grill stiffness are also determined to provide continuous contact with the HBM during impact. These two parts do not contribute much to the local deformation due to the relatively low stiffness. Since they usually do not have significant displacement in the vertical direction during impact, only the structural stiffness in the horizontal direction is defined.

This parametric model is validated by comparing simulations with the parametric vehicle model and with a detailed vehicle model, and good correlations have been obtained. Using the simplified vehicle model, the computation time of each HBM-to-vehicle impact simulation is reduced from 5.8 h to 1.3 h (6 CPUs on the Massively Parallel Processing) [30]. The reduction is necessary for response surface generation due to the need of a large number of simulation runs.

DESIGN OF EXPERIMENT & RESPONSE SURFACE GENERATION

Description of the Kriging Model and Sampling Strategy

The Kriging model is named after D.G. Krige, who applied empirical methods for determining true ore grade distributions from distributions based on sampled ore grades [31]. A detailed mathematical formulation of Kriging is given by Simpson [32]. Kriging models combine a regression term for the global portion of the model in conjunction with a correlation function for local departures and can provide success in approximation of highly nonlinear computer simulations [33].

The basic postulate of this formulation [32] is:

$$y(x) = f(x) + Z(x) \quad (1)$$

where y is the unknown function of interest, $f(x)$ is a known approximation (usually polynomial) function and $Z(x)$ is the stochastic component with mean zero and covariance:

$$\text{Cov}[Z(x^i), Z(x^j)] = \sigma^2 \mathbf{R}([R(x^i, x^j)]) \quad (2)$$

With L the number of sampling points, $\mathbf{R}$ is the $L \times L$ correlation matrix, and $R(x_i, x_j)$ is the correlation function between any two of the L sampled data points x_i and x_j . $\mathbf{R}$ is symmetric positive definite with ones along the diagonal. The correlation function $R(x_i, x_j)$ has different forms and the Gaussian correlation function is used in this study:

$$\mathbf{R} = \prod_{k=1}^n \exp(-\theta_k d_k^2) \quad (3)$$

where n is the number of variables and $d_k = x_k^i - x_k^j$, the distance between the k^{th} components of sample points x_i and x_j . There are n unknown θ_k -values to be determined as the correlation parameters.

The predicted estimate of the response $\hat{y}(x)$ is given by:

$$\hat{y} = \hat{\beta} + \mathbf{r}^T(x) \mathbf{R}^{-1} (y - \mathbf{f} \hat{\beta}) \quad (4)$$

where $\mathbf{r}^T(x)$ is the correlation vector (length L) between a prediction point x and the L sampling points, y represents the responses at the L points and $\mathbf{f}$ is a L -vector from the basis approximation function $f(x)$ in equation (1). The vector $\mathbf{r}^T(x)$ and scalar $\hat{\beta}$ are given by:

$$\begin{aligned} \mathbf{r}^T(x) &= [R(x, x^1), R(x, x^2), \dots, R(x, x^L)]^T \\ \hat{\beta} &= (\mathbf{f}^{-1} \mathbf{R}^{-1} \mathbf{f})^{-1} \mathbf{f}^T \mathbf{R}^{-1} y \end{aligned} \quad (5)$$

The estimate of variance from the underlying global model is:

$$\hat{\sigma}^2 = \frac{1}{L} (y - \mathbf{f} \hat{\beta})^T \mathbf{R}^{-1} (y - \mathbf{f} \hat{\beta}) \quad (6)$$

The maximum likelihood estimates for θ_k , $k = 1, \dots, n$, in equation (3), which is used to establish the Kriging model can be found by solving the following constrained maximization problem:

$$\max \Phi(\theta_k) = -\frac{1}{2} [L \ln(\hat{\sigma}^2) + \ln |\mathbf{R}|], \quad \theta_k > 0 \quad (7)$$

Therefore, the construction problem of Kriging model is turned into a nonlinear and unconstrained optimization problem. After θ_k is solved, the Kriging approximation model is established and estimate of the response $\hat{y}(x)$ can be obtained from equation (3), (4), (5).

In addition to being flexible due to the wide range of the correlation functions, the Kriging method can also provide a basis for a stepwise algorithm to determine the important factors for screening and building the predictor model [34].

To conduct the numerical experiments for the Kriging response surface models, the Latin Hypercube (LH) was chosen as the sampling scheme for the DOE study. It is first introduced by McKay in 1979 [35], as a statistical method for generating a stratified sample of parameter values from multidimensional distributions.

Assume that N sample points are to be determined for a k -vector variable $\mathbf{X} = (x_1, \dots, x_k)$. Then the range of each x_i ($i = 1, \dots, k$) will be divided into N equally probable intervals and sampled once from each interval. Let this sample be x_{ij} ($j = 1, \dots, N$). For the x_i ($i = 1, \dots, k$) component in $\mathbf{X}_j$ ($j = 1, \dots, N$), the components of the various x_i 's are matched at random. A detailed computer code and manual has been given by Iman [36].

As a structured quasi-random sampling strategy, the Latin Hypercube can generate random sample points ensuring that all portions of the vector space are sampled [35], and potentially nonlinear input and output relationships [37-38] can be represented in resulting response surfaces.

Learnings from Trial DOE Studies

To better understand the HBM-vehicle impact problem, several small-scale DOE studies (hereafter referred to as "trial DOE") are conducted in advance before the formal, large-scale DOE runs, using the same model setup (Figure 2). Different simplified parametric vehicle models (Figure 5) are created for performing the corresponding car-to-pedestrian impact simulations. Table 1 gives a summary of the trial DOE studies. The influence of sampling scope, design variable selection as well as variable range has been investigated.

DOE I and DOE II are carried out with the same design variables and variable ranges as that defined in the pre-