

Investigation on Pelvis Injury Indices Using a Human Finite Element Model

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ABSTRACT

For accurately predicting different fracture patterns of the pelvis frequently observed in pedestrian accidents with SUV/Mini-van, human finite element (FE) models have been developed. Although those models with failure representation can predict occurrence or nonoccurrence of fractures, quantitative estimation of probability of fractures is not possible. For human models without failure representation, typically stress or strain of elements is used for fracture prediction. However, numerous elements must be evaluated when fracture location is not predetermined.

This study investigated methodology for accurately predicting probability of pelvic fractures using a minimal number of output parameters. The hood edge and upper and lower parts of the bumper were chosen for representing vehicle fronts. These components were modeled using rigid surfaces with the stiffness of them represented by springs, to constitute 3-component models. FE simulations were run using a human FE model with failure representation and the 3-component models with the location and stiffness of the components varied. Some candidate fracture indices were determined from combinations of displacements, moments and forces. The results with pelvic fractures were used for determining most accurate injury indices based on the normalized variation of the injury index values at fracture. For validating the indices, simplified vehicle models representing the contours of representative SUV and Mini-van were developed using a modeling technique similar to that of the 3-component models. FE simulations were performed using these models and human models with and without failure representation. Pelvic fractures were predicted from eliminated elements for the human model with failure representation, and from the values of the injury index for the human model without failure representation. The results of the fracture prediction were compared for different

combinations of simplified vehicle models and stiffness, showing that the injury index determined in this study is capable of accurately predicting various patterns of pelvic fractures.

INTRODUCTION

According to accident statistics⁽¹⁾, 2,643 pedestrians sustained fatal injuries in Japan in 1997. Although the number of pedestrian fatalities had dropped to 1,721 in 2008, the rate of decrease was not as great as that of vehicle occupants. This has led to greater importance being placed on the protection of pedestrians for mitigating traffic accident fatalities. In addition, serious injuries to pedestrians also follow a similar trend, making pedestrian protection an important issue for mitigating serious injuries in traffic accidents. Distribution of injured body regions in pedestrian serious injuries shows that pelvis injuries accounted for 8.6% in 1997, while the percentage of pelvis injuries increased to 10.1% in 2008. This suggests that pelvis injuries are frequent enough to require attention in pedestrian serious injuries.

Most of serious pelvis injuries to pedestrians are pelvic fractures. Due to complex and highly three-dimensional nature of the geometry of the pelvis, a variety of fracture patterns have been identified⁽²⁾. Among those, pubic rami fractures are particularly frequent and their mitigation is very important. Ryan⁽³⁾ investigated 387 patients admitted to St. Vincent's Hospital in Australia with pelvic fractures due to traffic accidents, and found that 78.8% of them sustained pubic rami fractures. Edwards et al.⁽⁴⁾ investigated data from the Major Trauma Outcome Study (MTOS) and showed that 61.5% of pedestrian pelvic fractures were pubic rami fractures. As for the effect of car front shape on pedestrian pelvic fractures, Snedeker et al.⁽⁵⁾ conducted 5 PMTO(Post Mortem Test Object) impact tests against different car

shapes, three of them representing sedans and two of them representing vans. The pubic ramus fractured in all of the impacts against vans, suggesting that a higher hood edge may increase probability of pedestrian pelvic fractures.

Many studies have been conducted to estimate impact tolerance of the human pelvis. Cesari et al.⁽⁶⁾ conducted 55 dynamic impact tests by impacting the great trochanter with a spherical rigid impactor in sitting position, concluding that the tolerance was close to 10 kN of impact force from the results of force and acceleration time histories. Cavanaugh et al.⁽⁷⁾ conducted 12 side impact sled tests, and found that the peak force was a good injury predictor from logist analysis among the force, compression, velocity multiplied by compression, and sacral acceleration. Bouquet et al.⁽⁸⁾ conducted 11 lateral impact tests with 200 mm by 200 mm rectangular rigid impactor in order to strike both the iliac wing and the great trochanter, and concluded that an impactor energy was the best injury predictor. They also showed pelvis tolerance values for pelvis deflection, compression, and velocity multiplied by compression. Zhu et al.⁽⁹⁾ conducted 17 cadaveric side impact tests by the same means as those of Cavanaugh's tests, and concluded that the average force is a good predictor of pelvic injury based on the statistical analysis using sacral acceleration, maximum force, average force, compression, VCmax, VmaxCmax, FmaxCmax, and FavgCmax. Although these studies examined injury prediction capability of several different physical parameters, these were limited to the measurement capabilities of the experiments, therefore, there might be other response parameters that could better predict pelvis fractures.

Human finite element (FE) models have been developed to accurately reproduce pelvic fractures^{(10),(11),(12),(13),(14),(15),(16)}. Since a human FE model is capable of accurately reproducing the complex geometry of the pelvis, it is a suitable tool for analyzing the mechanisms of pelvic fractures in various fracture modes. It is also possible to predict occurrence or nonoccurrence of fractures by incorporating a failure model. However, it is not possible to quantitatively evaluate probability of fractures. In contrast, when a human FE model without a failure representation is used, fracture probability can be evaluated using stress or strain of elements. However, since it is generally impossible to identify the locations of fractures in advance, all of the output of every single element need to be evaluated, which is not generally practical.

This study therefore investigated methodology for accurately predicting probability of pelvic fractures using a minimal number of output parameters, with a focus on pubic rami fractures due to loading from vehicles with a high hood edge.

SELECTION OF INJURY INDICES

METHODOLOGY

Pelvic fractures in pedestrians were reproduced by conducting impact simulations using a human FE model representing a pedestrian and simplified vehicle models representing three components of a vehicle front end (3-component models). The results of the simulation cases in which pubic rami fractures occurred were used to determine an index for evaluating pubic rami fractures as well as its threshold.

The 3-component models were designed to represent a variety of vehicle front end geometries for reproducing iliac loading (direct loading of the pelvis) and greater trochanter loading (indirect loading of the pelvis via the acetabulum). The force-deflection characteristics of the hood edge and the bumper of the 3-component models were varied considering their great contribution to the pelvis loading. The 3-component models were crashed into a human FE model with a failure representation to predict occurrence or nonoccurrence of pubic rami fractures. Pubic rami fractures were identified by a collapse of cross-sections of the pubic rami. The time at which the cross-section collapsed was defined by comparing the time histories of fracture evaluation indices for the human FE models with and without a failure representation and identifying the time at which a significant difference in the indices became evident. Relative displacements around the pubic rami and section forces and moments at a cross-section of the pubic ramus were used as candidates for evaluation indices. Values of all the candidate indices were taken at pubic ramus fracture, and their variances in all FE simulations were quantitatively evaluated. The index with the smallest variance was considered most relevant to pubic rami fractures and was chosen as the fracture evaluation index.

3-COMPONENT MODEL

The shapes of the hood edge, bumper and lower bumper, which are major sources of loading on the lower body of a pedestrian, were modeled using rigid bodies. The force-deflection characteristics of each component were modeled using a spring connected to the rigid surface representing the component. The shapes of the components were averages of center section shapes of multiple vehicles. There are two major loading patterns of the pelvis of a pedestrian in lateral impact - one is indirect loading of the pelvis through the acetabulum due to femur loading, and the other is direct loading of the ilium. In order to reproduce these two different loading patterns, and to vary the time lag from bumper loading, the height and horizontal location of the hood edge were changed relative to the bumper. The horizontal location of the lower bumper was also changed relative to the bumper to represent various vehicle front end geometries, and the model without the lower bumper was also used to represent

the front ends of SUVs. The structure of the 3-component model and relative locations of the components used in this study are presented in [Figures 1](#) and [2](#), respectively.

The force-deflection characteristics of the different components were represented by giving a step function to the force-deflection characteristics of the spring connected to the rigid surface. The probability of pubic rami fractures was varied by changing the load level of the hood edge and bumper, which are the source of pelvis and femur loadings. Since the lower bumper hits the leg, insignificant sensitivity of the lower bumper loading to pubic rami fractures was expected and thus the load level of the lower bumper was set at 3 kN for all simulations. The load levels for the hood edge and bumper are given in [Table 1](#).

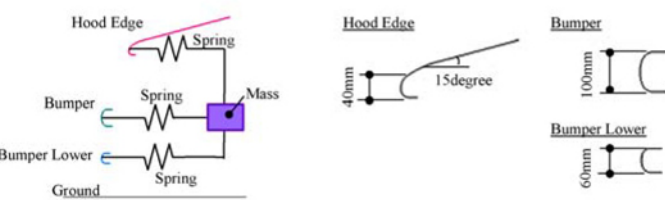


Fig.1. Structure of 3-Component Model

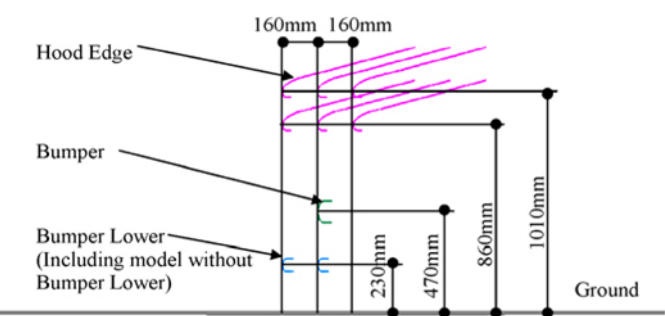


Fig.2. Location of Vehicle Components

Table 1. Force Level of Hood Edge and Bumper

Part	Force Level [kN]
Hood Edge	2,4,6,8,10
Bumper	2,4,6

HUMAN MODEL

A human FE model of an adult male developed by Kikuchi et al.[\(10\)\(11\)](#) was used in the current study ([Figure 3](#)). The geometry of this model was based on MRI images from a 35-year-old Japanese male volunteer with anthropometric parameters close to those of an average male. The model has been validated in terms of injury reproducibility of the pelvis, femur, tibia, fibula and knee ligaments. For characterizing the material property of the pelvic bone, a nonlinear elastic-plastic model incorporating strain rate sensitivity was used.

Pubic bone fractures were represented by using the element elimination option with an equivalent plastic strain criterion. The average element size of the pelvic bone was 8.9mm. The sacrum was modeled as a rigid body. The pubic symphysis was modeled using a non-linear elastic-plastic material model with no strain rate sensitivity and failure function. The average element size of the pubic symphysis was 5.0mm. The pelvis ligaments were modeled using tension only nonlinear elastic material model with no strain rate sensitivity and failure function.

The material models for parts of the human model for which injuries can be directly simulated incorporate a failure representation (Human Model A). These parts include the pelvis, femur, tibia, fibula and knee ligaments. Based on this model, another human model was created by disabling a failure representation for the pelvis (Human Model B). The results of the impact simulations under identical conditions using these two models were compared to identify the time of pubic rami fractures.

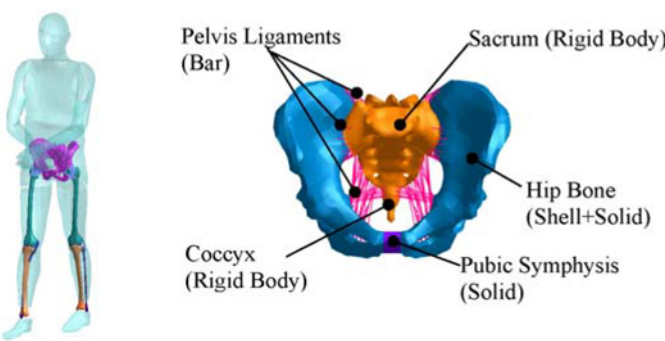


Fig.3. Human FE Model

IMPACT SIMULATION

Impact simulations were carried out by impacting the human model laterally with the 3-component models from its left side at a speed of 40 km/h. 18 shapes of 3-component models were used, including 6 different hood edges and 3 different types of lower bumpers (2 different horizontal positions and 1 without the lower bumper) ([Figure 2](#)). 15 force-deflection characteristics made up of 5 hood edge characteristics and 3 bumper characteristics ([Table 1](#)) were combined to create 270 different models. The right and left lower limbs of the human model were rotated 10 degrees about the hip joint in flexion and extension, respectively. [Figure 4](#) shows the typical kinematics and pelvis deformation from the simulations with a pubic ramus fracture.

<[figure 4](#) here>