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Modeling of human model for static pressure distribution prediction

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ABSTRACT

Vehicle comfort, the key factor that influences the purchase of automobile products, is becoming increasingly important. However, the processes of traditional empirical and experimental approaches to design a new, more comfortable seat is complicated, time consuming and costly. The finite element method could facilitate, accelerate and economize this process. In the present work, a complete human FE model is established based on the Hybrid III dummy, the appropriate element size of 10 mm was ascertained. The body segment mass was verified by comparing segment mass percentages obtained from this model with previous data. The further validation study of the human model was achieved via the human pressure distribution experiments over human-rigid seat interaction under three postures, the validation reveals that the simulation results agree well with the experimental data. On this basis, the human model was applied to predict the interactions between human body and an automobile seat, then the contact pressure distribution, additional information about the contact shear stresses distribution and stress distribution within the soft tissue were obtained through simulation. The human model presented in this paper can reflect the interaction between human body and automobile seat precisely.

Relevance to industry: The results deduced that the model is capable of realistically predicting pressure distribution, the present model allows the evaluation of seating comforts in a virtual phase of seat development, and the study can be taken as reference for vehicle seat design and biomechanical evaluation.

1. Introduction

Higher and higher demands on the performance of vehicles have lead to equally strong demands for sitting comfort of automobile. Manufacturers also treat vehicle comfort as a selling point. One of the most important indicators in vehicle comfort evaluation is sitting comfort. The foam seat, as the main interface of human—automobile interaction, strongly affects sitting comfort, and pressure distribution on the automobile seat has been regarded as the most important objective parameter for discomfort prediction (Nicol and Rusteberg, 1993).

Over the previous studies, a quantity of indicators have been put forward to characterize the ride comfort. Experiments were conducted to determine the relationships between objective measures and subjective ratings of comfort (Kyung and Nussbaum, 2008; Carcone and Keir, 2007; De Looze et al., 2003; Kolich, 2004). Extensive researches on the seat rely mainly on traditional methods that based on the experimental testing system (Chae et al., 2011; Wu and Rakheja, 2008; Carcone and Keir, 2007), however, these methods are time consuming and costly.

The development of computer technology provides a new method for this research, by building finite element (FE) models of human body or body parts, and then in combination with seat models, thereafter, the pressure and deformation distributions were obtained via the FE approach (Linder-Ganz et al., 2008; Siefert et al., 2008). Correspondingly, the most critical task is to develop an appropriate human model. FE models of body parts were developed by several researchers to simulate the interaction between human body and seat, Mohanty and Mahapatra (2014) and Tang et al. (2010) proposed 2-D buttocks and seat model, pressure distribution for static and dynamic condition were analyzed, respectively. The results revealed that the use of appropriate kind of foam material for seat could substantially reduce the pressure level and improve seating comfort. Oomens et al. (2003), Todd and Thacker (1994), Wagnac et al. (2008) and Verver et al. (2004) investigated the pressure distribution at ischial tuberosity and in-body stresses

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by using the established three-dimensional buttocks models, while ignored other body parts.

The major limitation of the human partial models is that it is difficult to perform accurate measurements of the interface, since the geometric of bony structures and soft tissues are simplified and incomplete. Therefore, some authors (Grujicic et al., 2009; Choi et al., 2006) have proposed the whole human models to predict the pressure with detailed and complete geometric description, while few validation studies have been explored. The Hybrid III 50th percentile male is the most widely used crash test dummy (Philippens et al., 2002; Noureddine et al., 2002), the dummy represents a male on the basis of his physiological characteristics in a sitting posture, and includes a fairly detailed anatomical description of bony structures. With appropriate modification and validation, the model is considered to have high instrumentation capability of predicting interface pressure.

The focus of this study was to set up a detailed and complete 3-D human FE model to predict pressure distributions, the model built in the paper is based on Hybrid III dummy, and the validation study of the body segment mass and body pressure distribution on the human-rigid seat interface were conducted, then the model was used in the prediction of the interaction between human body and automobile seat, the results reported in the study is useful for designing seat.

2. Human FE modeling

2.1. Modification of human model

Body pressure distribution is a result of the interaction between occupants and seats, it is crucial for accurate analysis to establish an appropriate human model. In this paper, a human model of 95th percentile Chinese male is built based on the Hybrid III 50th Percentile Male (close to 95th percentile of Chinese male) Crash Test Dummy, which originally developed by General Motors, and the first commercially available finite element model of the dummy was developed by FTSS. Currently, the human models is available for many FE codes. The model considered to have excellent biofidelity, there are still some differences in the anthropometric characteristics between Hybrid III dummy and the 95th percentile of Chinese male, and the dummy is used in the evaluation of automotive safety restraint systems, the details of the model were poorly simulated for the element size is large and coarse (The original element size is 40–50 mm). Therefore, it is necessary to modify the model elements and adjust the posture to meet the requirement of FE analysis.

The following preconditions must be fulfilled by human model to allow a numerical evaluation of static pressure. Firstly, the element size of contact areas between human and seat must match with each other. Secondly, different human tissues have different definition of stiffness properties, and different body parts have appropriate segment mass.

Firstly, the element size had to be reduced to proper value so that the result obtained from the relevant contact regions can reflect the pressure distribution precisely, and at the same time a relatively high computational efficiency is required. Four human-seat system models with different size grades (20, 15, 10, 8 mm) were set up, after that, the pressure distribution results among different models were analyzed and compared. The computation time for the four models is 21.4, 37.0, 37.6 and more than 55.1 h, respectively. Pressure results are displayed in Fig. 1, the results indicate that the smaller the element size is, the higher accuracy of the results will be acquired, but at the same time the calculation efficiency is much lower. Equally satisfactory results can be obtained with size grade of 10 mm and 8 mm, while the computation time for 8 mm grade is much more than that of 10 mm grade, it is obvious that 10 mm is the proper size of a better model in consideration of both computation efficiency and accuracy. Therefore, in this paper, 10 mm size element was used to mesh the human model.

For the skeletal system, great complexity exists in the structure, reasonable simplification is required: a) Ignore body parts that have little effect on the analysis, such as phalanges, toe, etc; b) Simplify irregular bones, such as upper and lower limb bone, both of which are simulated by using circular tube; c) Detailed modeling of significant body parts, such as the abdominal cavity, established two symmetrical ribs on left and right sides, then the front and back of the ribs are linked with the gladiolus and the thoracic spine, respectively. The skeletons and soft tissues portions were finally established, and shown in Fig. 2.

2.2. Material model

The material characteristic of different human tissues, including skeleton, muscle and nerves, etc, are various. All bones are modeled as rigid body, for their stiffness, compared to other body parts as muscles, is much higher. The skeleton are considered with linearly-elastic isotropic material with stiffness of $E = 16.7$ GPa, density of $\rho = 1700$ kg/m^3 and a Poisson's ratio of 0.3. For the soft tissue, all components are considered as the relevant muscle material, which shows strong nonlinear viscoelasticity incompressible characteristics. As a material approach for the muscle, a hyper-elastic isotropic incompressible law is used.

In previous studies, many researchers used the elastic Ogden (Oomens et al., 2003; Bosboom et al., 2001; Ogden, 1982) and Mooney-Rivlin (Verver et al., 2004; Grujicic et al., 2009) material models to describe the behavior of human soft tissues. The muscular portion of the human-body, in this study, was modeled using a Mooney-Rivlin hyperelastic isotropic model, whose strain energy function is defined as:

$$W_{MR} = C_1(I_1 - 3) + C_2(I_2 - 3) + C_3\left(I_3^{-2} - 1\right) + C_4(I_3 - 1)^2 \tag{1}$$

Here *I1*, *I2* and *I3* are the three invariants of the Cauchy-Green strain tensor. The right Cauchy-Green strain tensor, *C*, defined by:

$$C = F^T F \tag{2}$$

F is the deformation tensor, the invariants of the *C* tensor, I_1, I_2 and I_3, are defined respectively as:

$$I_1 = trace \cdot (C) \tag{3}$$

$$I_2 = \frac{1}{2}\left(trace^2(C) - trace\left(C^2\right)\right) \tag{4}$$

$$I_3 = \det(C) \tag{5}$$

Parameters A_3 and A_4 are functions of the coefficients A_1 and A_2:

$$A_3 = \frac{1}{2}A_1 + A_2 \tag{6}$$

$$A_4 = \frac{A_1(5\nu - 2) + A_2(11\nu - 5)}{2(1 - 2\nu)} \tag{7}$$

According to the strain energy function and the compression-force vs. displacement experimental data (Zhang et al., 1997), the values for A_1 and A_2 were assigned to: $A_1 = 1.65$ kPa, $A_2 = 3.35$ kPa. Other soft tissues, such as organs and brain which have little