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Anthropometric dependence of the response of a Thorax FE model under high speed loading: Validation and real world accident replication

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ABSTRACT

Finite element analysis is frequently used in several fields such as automotive simulations or biomechanics. It helps researchers and engineers to understand the mechanical behaviour of complex structures. The development of computer science brought the possibility to develop realistic computational models which can behave like physical ones, avoiding the difficulties and costs of experimental tests. In the framework of biomechanics, lots of FE models have been developed in the last few decades, enabling the investigation of the behaviour of the human body submitted to heavy damage such as in road traffic accidents or in ballistic impact. In both cases, the thorax/abdomen/pelvis system is frequently injured. The understanding of the behaviour of this complex system is of extreme importance. In order to explore the dynamic response of this system to impact loading, a finite element model of the human thorax/abdomen/pelvis system has, therefore, been developed including the main organs: heart, lungs, kidneys, liver, spleen, the skeleton (with vertebrae, intervertebral discs, ribs), stomach, intestines, muscles, and skin. The FE model is based on a 3D reconstruction, which has been made from medical records of anonymous patients, who have had medical scans with no relation to the present study. Several scans have been analyzed, and specific attention has been paid to the anthropometry of the reconstructed model, which can be considered as a 50th percentile male model. The biometric parameters and laws have been implemented in the dynamic FE code (Radioss, Altair Hyperworks 11©) used for dynamic simulations. Then the 50th percentile model was validated against experimental data available in the literature, in terms of deflection, force, whose curve must be in experimental corridors. However, for other anthropometries (small male or large male models) question about the validation and results of numerical accident replications can be raised.

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1. Introduction

1.1. Finite element models

The development of computer science, has allowed an increase of the use of numerical approaches such as finite element methods in order to understand physical mechanisms. These numerical tools are often used to extend and complete experimental investigations which are limited because of high financial costs. In the framework of biomechanics ethical issues are added to the costs of experimental tests. Thus, the use of simulation to avoid these limitations becomes essential in biomechanics investigations. In several contexts, like road accident or ballistic impacts, thoracic and abdominal trauma can occur, leading to injuries (rib cages, or soft organs) which are complex and which can be understood by using numerical simulations.

Lots of numerical models of thorax/abdomen system have been developed theses last decades.

The complexicity of FE model of the thorax in the literature varies according to their use, and the numerical computation ability: simulation of the skeleton without the soft tissues [1], and updated version [2–4], investigation of the effect of both static and dynamic loads [5], with more or less complexity of implemented material laws [6–8].

More recently, high dynamic simulations have been explored with developed FE models [9–13]. In another context, numerical simulations of thorax model coupled to implants have also been performed [14]. In addition to these models, thorax and abdomen FE models have been used in complete FE models of the human body [15–18].

The methodology of the numerical analysis using these models is very similar: creation of the FE model, validation against experimental data, and their use for different dynamic or static loads. Most of them have been developed in the framework of automotive industry, in order to evaluate the safety capability of vehicles for crash configuration.

Lots of models from the literature are close to a 50th percentile male, whose numerical responses have to be within experimental corridors. Specific methodologies are used to develop these corridors, based on different anthropometrical data of the tested cadaveric specimens [19].

For the development and the validation of subject specific FE models, and in order to take into account the different anthropometry of a population, the question about the development and the validation of a small and a large percentile can be raised: can a FE model based on any CT scans, be validated against experimental data whatever is the anthropometry?

Some research in the literature strive for answering to this question in developing age dependent models based on previous developed ones in order to obtained mid-sized male thorax or 5th percentile female thorax for example [20–25]. These developed models come from a 50th percentile geometry, and are modified in order to match a specific population. In addition to these geometrical modifications, properties of organs varied in order to reflect the wanted population.

In this context, in this paper, a new finite element model of the human thorax/abdomen system is developed, based on medical CT scans. Several CT scans have been studied and specific attention has been paid to the anthropometry of the subject, in order to match a 50th percentile model in terms of characteristics dimensions. Skeleton was meshed as well as the main internal organs. Material properties available from literature were implemented in the model for bones and soft tissues. Numerical replication of experimental tests was performed with the FE model, with a comparative analysis between numerical response and experimental corridors [19,26–29]. In the context of high speed dynamic impact such as ballistic impact, aforementioned experimental tests have been simulated with a 5th and 95th percentile FE model based on the developed 50th percentile model, in order to investigate their response and their ability to be validated. A ballistic impact from the literature was also simulated with the small, large, and mid-size models to study the influence of the morphology on computed mechanical parameters for a real world trauma.

2. Methods

2.1. Anthropometric point of view

The starting point in the development of biomechanical finite element models, is the 3D reconstruction of the geometry based on the grey level processing of 2D CT slices. 12 CT anonymised CT scans of the thorax/abdomen/pelvis system have been provided by the Medical Imaging Department of the Schweitzer Hospital, Colmar, France. The 3D reconstructions of the geometries were performed using two different methods. First, Scan2mesh module available in the Altair Hyperworks 10 pack was used to generate the geometry of organs and the two-dimensional mesh, which was directly imported into Hypermesh software. The second method was a manual segmentation. When automatic process led to a rough definition of the geometry of organs, manual image processing was performed to obtain organs contour. For each slice, contour lines were generated, and the final surface of the organ was created using the whole lines of each slice.

12 CT scan sets of images were available. Components' geometry of each CT scans were imported in Hypermesh software for the investigation of the anthropometry.

From an anthropometric point of view, different measures have been reported to select the appropriate CT scans which will lead to the development of a 50th percentile FE model of the human thorax. Several geometrical criteria from the literature were investigated.

All the CT scans were compared to available data from the literature in terms of characteristic body measurements [30,31]. Fig. 1 reports some body measurements and weight of the body from literature, compared with the selected CT scans.

In addition to these data, Bir et al. reported anthropometric data of cadaveric specimen, in terms of breadth, depth, and circumference [19]. Compared to the average calculated on male subjects in this study, the selected CT scan has only 15%, 6% and 5% difference in terms of thorax depth, breadth, and circumference, respectively.

These anthropometrical criteria allowed selecting the geometry for the development of a 50th percentile male FE