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Explicit finite element methods for equestrian applications

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Abstract

A virtual human body model (HBM), developed for vehicle crash simulations, was used to conduct a pilot study of dangerous accidents that occur in equestrian sports. It was performed to illustrate the potential that the explicit finite element (FE) HBMs have to improve rider safety and to assess the protective capacity of the safety vest. Four different questions were addressed:

1. When a rider is trampled by a horse, how does the risk of injury vary with chest impact location?
2. Does a safety-vest provide protection if the rider is kicked by a horse and does the protection vary with the violence of the hoof impact?
3. Can a safety-vest provide any benefit when the rider is hit by the horse after a rotational fall?
4. How does the risk for thoracic injuries vary when the rider falls off the back of a horse at different angles?

The HBM was the Total Human Model for Safety AM50 version 3.0 (Toyota Motor Corporation, Japan), improved for thorax injury predictability in a previous automotive project. The FE code was LS-DYNA (Livermore Software Technology Corporation, USA). Models of a generic safety vest, a horse impactor and a hoof were developed as part of this project. The risk of thorax injury was evaluated with stresses and strains measured for each rib, and the chest deformation criteria Dmax and DcTHOR.

The following results were obtained for each question:

1. The risk of injury was higher for hoof impacts close to the sternum compared to more lateral locations that had up to 25% less risk. Hence, this knowledge could be used to optimize novel safety-vest designs with HBM simulations.
2. Yes, the safety-vest provided protection against horse kicks, and it varied with the violence of the kick. Therefore, if the range of impact energy that occurs in real-world accidents is known, HBM simulations can be used to optimize the vest material properties.
3. No, the safety-vest did not provide any benefit when the horse lands on top of the rider. This conclusion suggests that safety measures should focus on preventing this type of accident, rather than designing personal protection for the rider.
4. When the rider falls with the head first, the number of predicted rib fractures increases compared to flat falls. However, the model predicts rib fractures for all of the falls simulated from a height of 1.5 meters for a rider without a safety vest.

To conclude, FE HBMs have the potential to improve equestrian safety and further studies on equestrian safety-vests designs are warranted.

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1. Introduction

Equestrian sports are popular and have a high incidence of injuries and fatalities compared to other sports. A recent review of the literature states that the most leading cause for rider injuries were fall accidents, followed by horse kicks or being stepped on by the horse [1]. In equestrian trauma, the most frequently injured body areas are reported to be the head, extremities and chest [1-3], their order of appearance changes depending on the study design. A US study [3] found that the injury patterns varied with age, where the most frequent injury for children (below 18 years of age) were upper extremity fractures, for younger adults (19 – 49 years of age) were concussion, and for older adults (above 50 years of age) were rib fractures. Wearing a riding helmet has been shown to be beneficial to reduce the head injury severity [3]. However, to the best knowledge of the authors, there is no study on

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the protective capacity of the safety-vests for riding that shows a safety benefit. There are many different safety-vest designs on the market and they are very likely to have a significant difference in safety benefit. Hence, there is a need to assess the protective capacity of safety-vests for riding.

Safety interventions can be assessed with real-world data (epidemiological studies). The major drawback is that the products must have been on the market some time before they show up in accident statistics. Ideally, the safety should be assessed before the products are launched on the market, to avoid preventable injuries due to faulty or less-efficient safety devices. In automotive safety, accident statistics are complemented with physical and virtual crash testing. Safety interventions and principles are evaluated with human substitutes, such as crash test dummies. Nowadays, most product development is done virtually and safety is assessed with virtual crash testing using explicit finite element (FE) simulations. Therefore, there have been many international research efforts to create biofidelic human body models (HBMs) that are validated to predict injury due to impact loading. These models are promising to study other impact scenarios, such as equestrian accidents.

This pilot study aims to assess the potential that FE HBMs have to improve rider safety with respect to thoracic injuries and to evaluate the protective capacity of a safety vest. Four different questions were chosen based on the relevance to rider safety:

1. When a rider is trampled by a horse, does the risk of injury vary with chest impact location?
2. Does a safety-vest provide protection if the rider is kicked by a horse and does the protection vary with the violence of the hoof impact?
3. Can a safety-vest provide any benefit when the horse lands on top of the rider after a fall?
4. How does the risk for thoracic injuries vary when the rider falls off the back of a horse at different angles?

2. Method

All simulations were performed with the FE solver LS-DYNA (LSTC Inc., Livermore, CA, USA), surface processing was done with CATIA version 5 (3DS Dassault Systèmes, Paris, France), meshing with Hypermesh (Altair Engineering, Troy, MI, USA), and post-processing with LS-PREPOST (LSTC Inc., Livermore, CA, USA) and MATLAB (The Mathworks Inc., Natick, MA, USA). The HBM used was the Total Human Model for Safety AM50 version 3.0 (Toyota Motor Corporation, Japan), subsequently improved and validated for thoracic response [4], hereafter called THUMS.

The risk for thorax injury was evaluated with previously developed risk curves for an older population [5-6] focusing on abbreviated injury scale (AIS) 2+ injuries, i.e. two or more rib fractures. Four different criteria were used; the shear stress (τ) and maximum principal strain ($\varepsilon 1$) in the rib cortical bone, the maximum chest deflection (Dmax) [7] and differential deflection criterion (DcTHOR) [8]. Dmax measures the maximum relative chest deflection at five points on the ribcage, where 100% means that the chest was completely compressed at some point and 0% means no compression. DcTHOR measures the maximum deformation between the same points as Dmax, but with emphasis on asymmetric deformation by adding terms measuring differences in deflection between the left and right side of the ribcage. The nodes used for the displacement measures were mid sternum (#89213524), upper left (#89200050), lower left (#89206698), upper right (#89220050), lower right (#89226698) and ninth thoracic vertebra (#8913156), according to [5].

2.1. Created models

The horse hoof was modelled as an oval shaped rigid shell plate (135 x 140 mm). A mass of 125 kg was added to the hoof, which represents a fourth of the mass of a 500 kg horse.

A simplified model of a safety-vest (Fig. 1), typical of those worn by horse riders [9], was created with a foam core (thickness 20 mm) of solid hexahedral elements. It was covered by an inner and an outer surface nylon fabric (thickness 0.5 mm) of shell elements, with nodes merged to the foam core. The inner nylon fabric was meshed based on the THUMS external torso geometry to provide a perfect fit. Two layers of solid elements were offset from the inner surface to mesh the foam core. The outer nylon fabric was created on the outer faces of the foam core elements. The nylon fabric was modelled as a linear elastic material and the foam core was modelled as a low-density foam (Fig. 2). Material data are listed in Table 1, and were taken from online sources [10, 11]. A sliding contact was defined between THUMS' chest and the vest.

Table 1. Material properties for the simplified safety-vest model.

Material	LS-DYNA material model [1]	Density [kg/mm^3]	Young's modulus [GPa]	Poisson's ratio	Stress-strain relationship	Ref.
Foam core	MAT_057	2.40e-7	-	-	Linear	[10]
Nylon fabric	MAT_001	1.00e-6	2.00	0.32	Fig. 2	[11]