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Experimental and finite element analysis for prediction of kidney injury under blunt impact

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ABSTRACT

Kidneys are third most injured organs in abdominal trauma after liver and spleen; this study therefore is an attempt to understand the behaviour of kidneys under blunt trauma. Dynamic impact tests were performed on 20 fresh porcine kidneys to study the injury propagation in the organ, and the acceleration of the impactor was measured. A kidney model was developed with structural details like capsule and cortex. The kidney cortex was modelled with solid hexahedral elements and the capsule was modelled with quadratic shell elements. The material models for the capsule and cortex were used from the experimental data reported in our previous study. The developed model was calibrated using previous and current experimental results to reproduce the injuries of the organ in terms of acceleration of the impactor, and the injuries sustained by the organ during the experiments. The developed kidney model is observed to be robust and can be integrated with the available human body finite element models to simulate accidents and to predict or simulate injuries.

1. Introduction

Blunt abdominal trauma is most common in poly-traumatised patients and after neurocranial trauma it is one of the major determinants of early death in these patients (Elhagediab and Rouhana, 1998). Evaluating patients who have sustained blunt abdominal trauma remains one of the most challenging and resource-intensive aspects of acute trauma care. Research by Augenstein et al. (2000), Rouhana (2002), Lau et al. (1987) and Carmona et al. (1982) reveals that in vehicle trauma, the liver, spleen and kidneys sustain the most fatal injuries after the brain. The liver and kidney are the most studied human body organs after the brain; however there are no sophisticated finite elements models available for abdominal organs as that of brain. From a biomedical aspect to develop virtual simulators and surgical tools, it is important to have accurate models of the abdominal organs which can replicate a realistic mechanical behaviour of respective organs.

Snedeker et al. (2002) developed a hollow human kidney model and tried to simulate its behaviour using data of Rhesus monkey kidney under compression from Melvin et al. (1973). Nicolle et al. (2012) reported that some finite element models of the whole human body used in automotive safety research have been developed with a detailed abdomen: the WSU model from the Wayne State University (Lee and Yang, 2001) and its derivative TAKATA model (Zhao and Narwani, 2005, 2007), the Ford model from Ford Motor Company (Ruan et al., 2003, 2005; El-Jawahri et al., 2010), the H-model from ESI Group (Huang et al., 1994), the Humos model from the HUMOS European Consortium (Vezin and Verriest, 2005) and the THUMS model from Toyota Motor Corporation and Toyota Central R&D (Iwamoto et al., 2002; Shigeta et al., 2009. Vavalle et al. (2013) have reported sled test simulation on GHBMC (Global Human Body Model Consortium) model. In all these models the liver, kidneys and spleen are modelled separately while the rest of the abdomen including stomach, pancreas, small and large intestine, gallbladder, bile ducts, ureters, rectum and adrenal glands are usually modelled together as one or several bags under pressure (Lee and Yang, 2001) or an interstitial continuous solid mesh (Ruan et al., 2005). Usually a simple elastic or linear viscoelastic model is chosen to represent the mechanical behaviour of these organs. Therefore, these models are not able to describe the nonlinear stress strain relationship observed by the actual soft tissue. In the WSU model (Lee and Yang, 2001) and TAKATA model (Zhao and Narwani, 2005), the Zener material model is made nonlinear by making the model parameters dependant on the volume change but not on the deformation. And although the liver, kidneys and spleen are well detailed geometrically in the Ford model, there is no distinction made in their

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material properties. This illustrates how important it is to develop models of the abdominal organs which could reproduce their kinematics during impact accurately.

The literature review revealed that quite a few studies were done to characterize the kidney tissues using various experimental protocols viz. tension, compression, shear, transient elastography, ultrasound, etc. (Snedeker et al., 2005a, b; Farshad et al., 1999; Nicolle and Palierne, 2010; Nicolle et al., 2010; Miller, 2000). Snedeker et al. (2005a) found the human kidney cortex is less stiff as compared to porcine kidney cortex from the static tests, which is justified as the human kidneys were obtained from diseased subjects. Whereas Snedeker et al. (2005b) observed human renal capsule to be stiffer than porcine renal capsule at higher strain.

The results of the characterisation experimental tests of capsule and cortex were previously published in Umale et al., 2013. Using the material properties from the characterization tests the FE model of the organ was developed. Experiments were performed to study the behaviour of kidney under dynamic loading and the results from these experiments were used to optimise the behaviour of kidney finite element model under impact.

2. Materials and methods

The methodology of the study consists of characterization experiments on renal capsule and renal cortex and developing material models for each. The next step involves using the developed material models and the geometries to develop finite element models of the kidney with cortex and capsule. Dynamic experiments are performed by impacting the kidneys with a solid metal impactor. The characterisation and impact experiments were used to calibrate the FE model, by reconstructing the same impact results in the LS Dyna environment. For the experiments porcine kidneys were used in this study as the human surrogates as they have almost indistinguishable anatomically (Snedeker et al., 2005a,b). The human and porcine kidneys are so similar that research is also being carried out to use porcine kidneys for transplant in human (Xia et al., 2013).

3. Experimental testing

The impact experiments were carried out on 20 kidneys of adult female pigs weighing 30–35 kg, obtained from Institut de Recherche contre les Cancers de l'Appareil Digestif, Strasbourg, France (IRCAD). The organs were removed from the porcine body by performing total nephrectomy on anaesthetised specimen, as per ethical standards. At the time of harvesting the organs, renal vessels and ureter were transfixed with a surgical thread so that the blood and urine remained inside so that the pressure was near to natural. The kidneys were then wrapped in a surgical towel, soaked in saline solution, packed and transported to laboratory within 30 min in an ice box maintained at a temperature of 4–6° C. All the tests were carried out on fresh organs without preconditioning, at room temperature (about 24 °C) and within 2–4 h of post-mortem, to reduce the post-mortem effect as much as possible.

Before performing the experiments the mass and dimensions of each of the kidneys were measured as shown in Fig. 1(a). The maximum length of the kidney was measured, the width was measured at two locations and the thickness of the kidney was measured using a vernier calliper with an error of ±1 mm. The average height, width at top (W1), width at bottom (W2) and thickness were measured as 92±7 mm, 49±4 mm, 45±5 mm, and 23±3 mm respectively. The average mass of the 20 kidneys on which tests were performed was 69.8±15.5 g. The dimensions and mass were used to incorporate into the FE model to attain the same geometry of the kidneys.

The schematic representation of the experimental setup used for the impact tests is shown in Fig. 1(b). The setup consisted of an impactor guide, which was controlled by a pneumatic mechanism. Just before the point of impact, the velocity of the impactor was measured using a laser sensor. After a few trial iterations of impact on some kidneys, it was observed that a velocity of 1.5 m/s with the impactor of mass 2.5 kg was sufficient to injure the organ. Therefore, the impactor guide was lifted up to a certain height, and released under the influence of gravity to get the impact velocity between 1.5 and 2 m/s at the point of contact. The impactor was placed on the guide and was tied with a rope, to constrain the motion of the impactor after impact. The impactor was mounted with a KISTLER 3D accelerometer, which assisted in recording the acceleration during impact, at 50 kHz. The impactor weighing 2.5 kg was released along with the guide to impact the kidney which was placed on the rigid anvil as shown in Fig. 1(b). The acceleration of the impactor was recorded for the impact, and the injury suffered by the organ was noted after the impact.

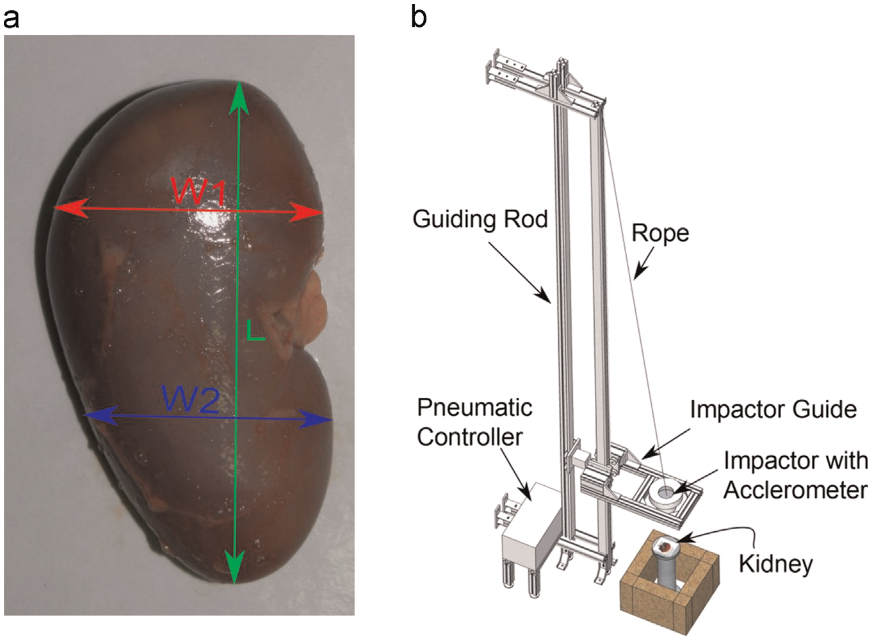

Fig. 1. (a) Measurement of dimensions of the kidney. (b) Schematic representation of the kidney impact test setup.

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