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Assessment of the ultimate strain of the hepatic capsule for the prediction of liver surface laceration

K. Bruyère^{1*}, A. Bel-Brunon², C. Jayyosi¹, A. Chenel^{1,4}, M. Coret³, C.J.F. Kahn⁴, C. Masson⁴

I. INTRODUCTION

In the field of road safety, the prediction of abdominal injuries is a relevant issue, especially considering rear-seat passengers such as children, elderly or obese individuals [1-2]. Among abdominal organs, the liver is particularly vulnerable due to its weight and location. Moreover, the liver which is highly vascularized has a high level risk of severe hemorrhage when injured. Considering its three main components - parenchyma, capsule and a dense vascular network – this complex organ has three main types of injury: hematoma, laceration and vascular failure [3]. The liver also has a high level of variability in terms of geometry and mechanical properties which makes it difficult to model. The variability of mechanical properties of hepatic tissues is closely related to individual variability and to potential diseases of patients such as the case of steatotic liver due to obesity or diabetes, for which parenchyma is especially fragile.

Global injury criteria were established on whole pressurized organs in terms of impact energy [4], impact velocity and peak pressure [5]. Local mechanisms of vascular/parenchyma injuries during a freefall and severe frontal deceleration were also highlighted [6] but not quantified in terms of local criteria.

The present study focuses on liver surface laceration, involving capsule and parenchyma. The hypothesis of the authors is that this type of injury occurs because of an excessive pressure and thus an important tension on the liver surface during an impact. Thus, local failure criteria of the capsule and superficial parenchyma must be defined in view of the prediction of surface laceration occurrence.

For a few years, the co-authors, members of the French research network Impact Biomechanics Research Group, studied the mechanical behavior of hepatic tissues up to failure. In a first step, uniaxial and equibiaxial tensile tests were performed on isolated samples of capsule-parenchyma and capsule in order to quantify the ultimate mechanical properties of the capsule. In a second step, the capsule pretension before sampling was assessed on isolated liver under various internal fluid pressures. During all these tests, the surface strain fields were measured on the hepatic capsule by digital image correlation.

II. METHODS

Capsule under uniaxial loading

Quasi-static uniaxial tensile tests were performed on 14 isolated I-shaped samples of superficial capsule-parenchyma taken off from 3 human fresh livers. Considering the superficial hepatic tissues as isotropic, no attention was paid to the samples' orientations. Due to manual cutting, geometries of samples were different but close to 5 mm thickness, with a gage length between 50 – 70 mm and a width between 10-15 mm. Tests were performed up to failure at 5mm/min giving a strain rate between 10^{-3} and 10^{-2} s⁻¹. Full strain field was measured on the capsule during the tests using 2D image correlation (Icasoft®). To separate the capsule and parenchyma behavior, a model of 2 springs in parallel was applied. More details of the protocol can be found in [7].

Capsule under equibiaxial loading

In order to load the capsule in a more realistic manner regarding the objective of predicting superficial laceration by overpressure, a protocol of equibiaxial loading by inflation was developed. Inflation was applied by air on circular samples, clamped on a circumference diameter of 25 mm, with a strain rate close to

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10^{-2} s^{-1} . Ten samples from 1 human fresh liver were tested up to failure. Full strain field was measured during the tests using 3D surface image correlation (Vic3D®). More details of the protocol can be found in [8].

Capsule on pressurized liver

In order to take into account boundaries and loading conditions of the superficial hepatic tissues in a more realistic manner, the initial pre-strain of a tensile test sample was measured before sampling. One isolated embalmed liver was sustained by diaphragm and pressurized with water injected via the portal vein in a quasi-static manner. Full strain field was measured (Vic 3D®) at the right lobe liver surface during pressure loading and then after sampling. Taking the final sample image as the reference image allowed us to assess pre-strain field.

III. INITIAL FINDINGS

Full strain field measurements during the tests on isolated samples allowed the quantification of an ultimate local strain. From uniaxial tensile tests, the ultimate first principal Green-Lagrange E1 was 32.6 % on average (SD 13.8%, n = 14). From inflation tests, E1 was 50.5% on average (SD 10.8%, n = 10). An example of full strain field measured on the last image before failure during an inflation test is given (Figure 1).

Full strain field measurement on a pressurized liver before and after sampling of a rectangular piece of superficial hepatic tissues shows a pre-strain of the capsule up to 17% in the medio-lateral direction of the liver (first principal Green-Lagrange E1) (Figure 2) and up to 8% in cranio-caudal direction (second principal Green-Lagrange E2).

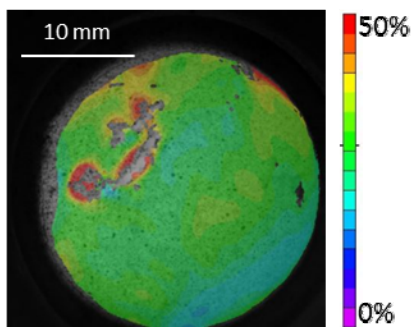


Fig. 1 : Inflation test on the hepatic capsule, first principal strain field E1 before failure

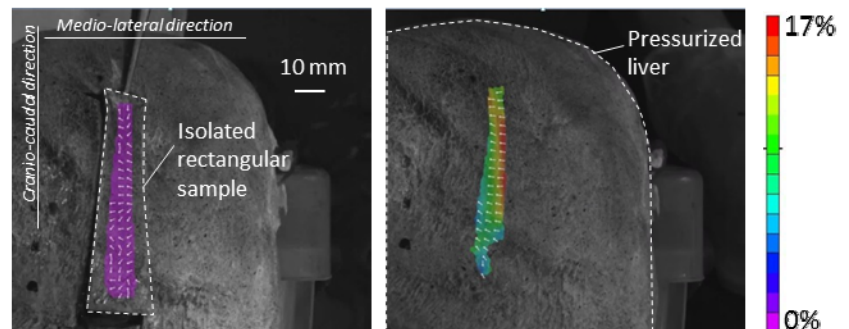


Fig. 2 : Pre-strain of the capsule on pressurized liver, first principal strain field E1

IV. DISCUSSION

Different values of ultimate E1 were obtained from tests on isolated samples under uniaxial and equibiaxial loading. This may be due to the use of two-material samples for the uniaxial tests or to the variability of the mechanical behavior between samples. To improve the knowledge on this variability, other uniaxial and equibiaxial tests associated to a simultaneous observation of the capsule microstructure were performed [9].

The assessment of the ultimate strain of the capsule on isolated samples is a first step, but the initial pre-strain of this tissue *in vivo* must also be evaluated in view to define a pertinent value of the strain as failure criterion. In this perspective, we showed the feasibility of the measurement of this pre-strain on an isolated liver under pressure. This protocol will be improved and applied on a liver *in situ* in a next step.

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