Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 9 Issue 1, January - 2022

Strain Rate Dependency Of Human And Porcine Spleen Material Properties

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***Abstract*— Splenic injuries resulting from blunt force trauma and other dynamic loads are commonly life threatening. Finite element modeling is a tool used to predict these injuries but using accurate material properties is essential to obtaining useful results. Further characterization of spleen material properties is needed as current data are limited and often not appropriate for the intended purpose. Four human and 32 porcine spleens were procured and subjected to a nondestructive unconfined compression protocol using rates from 1%/s-1000%/s, a destructive unconfined compression protocol using rates 1%/s-500%/s, and a nondestructive probing protocol at the rates of 1%/s and 25%/s. The elastic modulus was calculated for both nondestructive protocols and the failure stress and strain was measured in the destructive protocol. Numerical models were developed that describe the stress-strain relationship and the strain rate dependence of the material properties. No differences were found between human and porcine spleens for the elastic modulus, which was found to be strain rate dependent and increased from 0.008 MPa at 1%/s to 0.036 MPa at 1000%/s. A 136% increase in stiffness was observed for the probing as opposed to the unconfined compression protocol. Failure stress was strain rate dependent for both human and porcine spleens ranging from 0.083 MPa at 1%/s to 0.28 MPa at 500%/s for the porcine specimens. No strain rate dependency was observed for failure strain for either host. The results from this study suggest that strain rate be considered when choosing material properties for modelling, that the testing procedure should correspond to the expected load, and that care must be exercised when substituting porcine spleen mechanical properties for human, particularly when predicting damage.**

Keywords— spleen; tissue testing; failure properties; strain rate; elastic modulus; porcine vs human

I. INTRODUCTION

Abdominal injuries can put victims of traumatic situations into grave danger as they can be hard to diagnosis. In a study observing patients admitted for abdominal trauma the spleen was the second most frequently injured organ [1]. Experimental and analytical studies can both be used to develop a better understanding of the injury mechanism during blunt force impact events, leading to better diagnoses and prediction of abdominal injuries Detailed finite element models are commonly used to predict injury due to car crashes, blunt force trauma, and blast loading, to help plan surgeries, and in forensic biomechanics etc. [2-13].

Finite element models require accurate material properties to produce accurate simulations. However, accurate material properties for many of the human abdominal organs are scarce or nonexistent in the literature. Additionally, given the dynamic nature of many of the intended applications, the effects of strain rate on the mechanical behavior should be considered. Previous research on human abdominal organs have found a strain rate dependency [14-19]. However very few studies have identified the strain rate effects on the material properties of the human spleen, and none have yet to establish a numerical relationship. Stingl (2002) only tested the spleen capsule while Kemper (2012) tested the spleen capsule and parenchyma plus capsule with both studies loading the tissue in tension [20,21]. These studies investigated the different structures that together make up the spleen but have not looked at the entire organ as an intact unit.

In order to characterize the complete response of the spleen, one step is to study the whole intact organ in a similar fashion to the desired traumatic situation, and this is of particular importance for the spleen since models often do not distinguish between the parenchyma and capsule. The difference in organ mechanical properties when considering the entire intact organ versus individual components or samples has been previously identified [17-19]. The spleen is housed within the abdominal cavity on the left-hand side between the 9th and 11th thoracic vertebrae. If force is applied directly to the abdomen the spleen is compressed by the surrounding structures. To determine material properties for models that simulate traumatic loading using a monolithic spleen material model the intact organ must be tested intact under compression. Furthermore, to allow for damage predictions, the load or deformation at which failure occurs is also required and has not been studied in the literature.

Due to the challenges in obtaining specimens for studying human spleen material properties porcine spleens are often used as a proxy [22-25]. Only one study, Kemper (2012), has investigated the tensile material properties of the human spleen and compared them to a study, Uehara (1995), that was conducted in a similar manner using porcine specimens [21,26]. The study concluded that the properties obtained from human specimens differed from porcine, however it is also pointed out within the article that there were some assumptions made in order to compare the two studies. No research has been conducted that fully investigated the feasibility of using porcine specimens instead of human spleens to determine a range of material properties through a direct comparison of the two hosts using an identical methodology.

The goal of this study is to characterize the response of the spleen considering properties typically used in numerical modeling, such as the elastic modulus (E), failure stress (σ_f), and failure strain (ε_f) of the intact porcine and human spleen to various strain rates using probing and unconfined compression protocols Specifically, the aims are to: i) determine the feasibility of using porcine spleen as a model for human spleen; ii) compare the results using the two testing protocols; iii) evaluate the impact of using intact organs, and iv) quantify the tissue properties at different strain rates.

It is hypothesized that the elastic modulus of an intact spleen will differ between two protocols, that failure stress, failure strain, and elastic modulus will increase as strain-rate increases, and that the properties derived from intact organ tests will differ from those performed on partial specimens. Finally, it is hypothesized that porcine spleen material properties are a suitable substitute for human spleen mechanical properties.

II. METHODS

A. Specimens

Material testing was performed on spleens from two different hosts, human and porcine. Three cadavers were procured from the Medical College of Wisconsin. A splenectomy was performed on all three cadavers within 48 hours after death with capsule and vasculature left intact. An additional human spleen was acquired from the National Disease Research Interchange. All human tissue was tested within 72 hours from time it was acquired. All donors were screened and were free of any transmittable diseases. Thirty-two porcine spleens were received from a government inspected local slaughterhouse. Professional butchers performed the splenectomy leaving the entire organ intact. Organs received from the slaughterhouse were obtained from porcine being slaughtered for other purposes and thus no animals were euthanized for research purposes. Tissue received from the slaughterhouse was inspected to ensure the capsule and vasculature was left intact. Porcine testing was completed as soon as possible after receipt (within 7 days). All specimens were stored in an airtight bag filled with a physiological base solution in a refrigerator set at 4 degrees Celsius for preservation. Age and size of all specimens used can be found in the supplemental information

B. Experimental Protocol

Two types of tests were performed: unconfined compression and probing. Unconfined compression testing was performed using two separate methods: nondestructive and destructive. Both methods were performed using an MTS with a 15 kN load cell (model 661.19F-03) with an accuracy a fraction of a newton. Nondestructive testing involved compressing the spleen between two plates while simultaneously measuring forced and displacement (Fig. 1). Different sized compression plates were used for human and porcine spleen tissue to ensure the plates were large enough and did not flex during testing. The spleen was oriented with the posterior surface resting on the compression plate and the force was applied to the anterior surface of the organ. This orientation allows for a loading direction that is similar to how compression would be applied in a frontal blunt impact to the abdomen. The compressive force was applied to the spleen up to 35% (±5%) strain using the rates from 1%/s to 500%/s. No preconditioning was used, however all tested loading rates were randomized in order to eliminate any effect of testing order. A long stroke arm of the MTS was used to eliminate the inertial forces observed due to the onset of motion. Once 35% strain was reached on the specimen the plates released the applied force at the loading rate. Specimens were allowed to return to their initial height (±1%) prior to any additional testing to ensure no damage occurred. Height was measured using calipers and confirmed using the MTS. Destructive testing followed the same protocol; however, the compressive force was applied until the specimen failed. Failure was defined as a 5% drop in applied force or no increase of force after a 3% increase in strain.

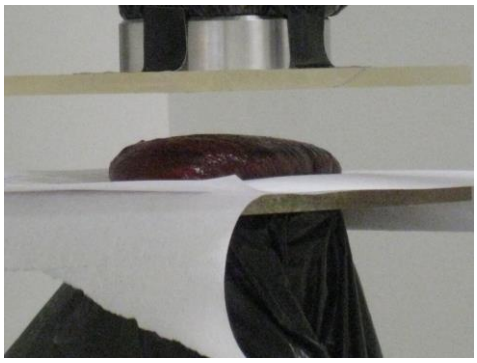

Fig. 1. Human spleen placed between the compression plates of an MTS

The probing protocol took place either before or after the nondestructive compression protocol and before the destructive testing protocol. As in the nondestructive compression protocol, a force was applied to the organ at a constant rate up to 31% strain and then relaxed at the same rate. The spleen was placed in the same orientation as for the compression

protocol, but force was applied with a flat end probe with a surface area of 126.7 mm^2 (Fig. 2). The probe was place at the thickest point of the spleen for both human and porcine specimens to enable the tissue to have complete coverage of the probe at initial contact. Force and displacement were measured using the Mark 10-EML test stand.

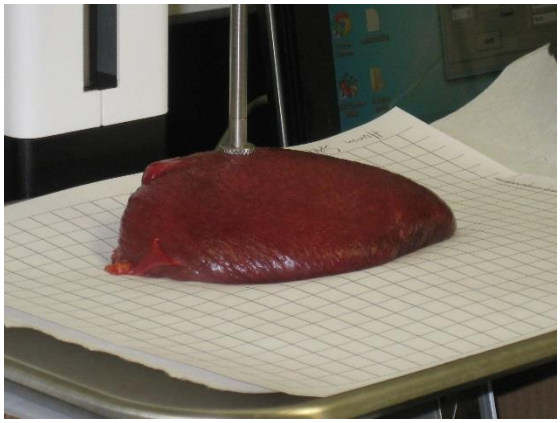

Fig. 2. Human spleen placed on the Mark 10-EML test stand for the probing protocol

C. Data Analysis

In both protocols the force and displacement were measured simultaneously during the tests. Engineering stress was computed using Eq 1 and Eq 2 for the two protocols. Engineering strain was calculated using Eq 3. Engineering stress and strain were chosen since obtaining the exact area during testing was not possible and their general use in the literature [27]. Modulus was determined by calculating the slope of the stress-strain curve in the terminal region of the response at the highest measured strain.

$$\sigma_{ND} = \frac{Force}{Surface\ Area_{Specimen}} \quad (1)$$

$$\sigma_P = \frac{Force}{Surface\ Area_{Probe}} \quad (2)$$

$$\varepsilon = \frac{\Delta Height}{Height_{Initial}} \quad (3)$$

A mathematical model (Eq. 4) was used to describe the stress-strain relationship that was observed in the experimental testing [28]. The variables used within the model are the elastic modulus in the toe region (E_{toe}), the elastic modulus in the terminal region (E_{term}), the center strain of the inflection region (ε_c), and a parameter describing the curvature of the inflection region (ψ). For each of the trials the parameter values that best fit the experimental curves were determined. An equation was also developed to determine the relationship between the material properties with strain rate (Eq.5).

$$E = \{1.0 + tanh(\psi[\varepsilon - \varepsilon_c])\}\{(E_{term} - E_{toe})/2.0\} + E_{toe} \quad (4)$$

where E is the current elastic modulus and ε_c is the current strain.

$$Property = a + b\dot{\varepsilon}^c \quad (5)$$

where a, b, and c are parameters that vary with each property type (elastic modulus, failure strain, failure stress), and $\dot{\varepsilon}$ is the strain rate. The values for each parameter were found using the solver function in Microsoft Excel.

Changes in the material model parameters between different strain-rates were analyzed. All data was confirmed to be normally distributed using an Anderson-Darling test for normality. A one-way ANOVA was used to test the factor of strain rate for all tests for each host. A two-tailed two-sample Welch's t-test, variance was not assumed equal, was conducted at each of the strain rates that were tested on both hosts to test whether human and spleen material properties were statistically different. An alpha value of 0.05 was set for both statistical tests that were performed.

III. Results

A. Stress-Strain Behavior

Human and porcine spleens were observed to have different stress strain curves (Fig. 3). Human spleens had a shorter toe region (maxed out at 5% strain) before the inflection point than the porcine hosts (maximum of 20% strain). A numerical material model (Eq. 4) was used to describe the stress-strain curves of both human and porcine spleens. Table 1 contains the values of all parameters for a quasi-static rate,1%/s, and a dynamic rate, 25%/s, for both human and porcine spleens. An example of the stress strain curve of the experimental versus the modeled results is shown in Fig. 3.

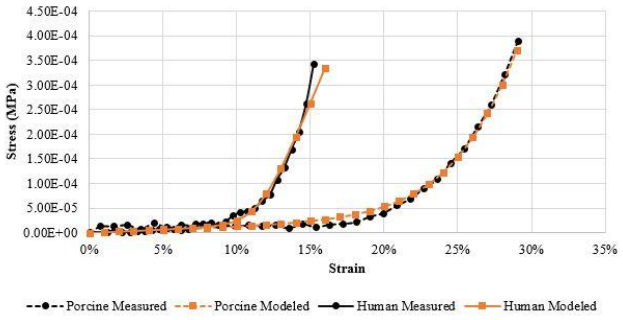

Fig. 3. Representative measured and modeled stress-strain curves of the human and porcine spleen in unconfined compression at a rate of 25%/s

Small differences that were not statistically significant were observed between the human and porcine spleen elastic modulus in both probing and unconfined compression protocols ($p>0.05$). At both testing rates, the standard deviations overlap between the two organ hosts (Fig. 4). Human spleen specimens averaged 0.004 MPa and 0.007 MPa at 1%/s and 25%/s in unconfined compression respectively. Porcine spleen averages 0.008 MPa and 0.01 MPa for the rates of 1%/s and 25%/s in unconfined compression respectively. Human spleen specimens averaged 0.014 MPa and 0.018 MPa at

ASD Table 1. Average and standard deviation of the modeled variables for both human and porcine specimens in unconfined compression

Human	1 %/s	25 %/s
E_{toe} (MPa)	0.0002 (±0.0001)	0.0002 (±0.0002)
E_{term} (MPa)	0.004 (±0.0012)	0.007 (±0.004)
ε_c	0.09 (±0.02)	0.12 (±0.03)
ψ	48.1 (±28.9)	28.1 (±10.1)
R^2	0.94 (±0.02)	0.95 (±0.02)
Porcine		
E_{toe} (MPa)	0.0001 (±0.00011)	0.0001 (±0.00019)
E_{term} (MPa)	0.008 (±0.005)	0.010 (±0.004)
ε_c	0.30 (±0.12)	0.27 (±0.02)
ψ	13.6 (±9.19)	14.1 (±5.09)
R^2	0.98 (±0.04)	0.96 (±0.04)

1%/s and 25%/s in the probing protocol respectively. Porcine spleen averages 0.015 MPa and 0.02 MPa for the rates of 1%/s and 25%/s in the probing protocol respectively. The elastic modulus was increased from the unconfined compression to the probing protocol for both hosts at both quasi-static and dynamic rates. Human spleen became 220% and 160% stiffer from the unconfined compression protocol to the probing protocol at 1%/s and 25%/s respectively (Fig. 4). Porcine spleen became 73% and 90% stiffer from the unconfined compression protocol to the probing protocol at 1%/s and 25%/s respectively (Fig. 4).

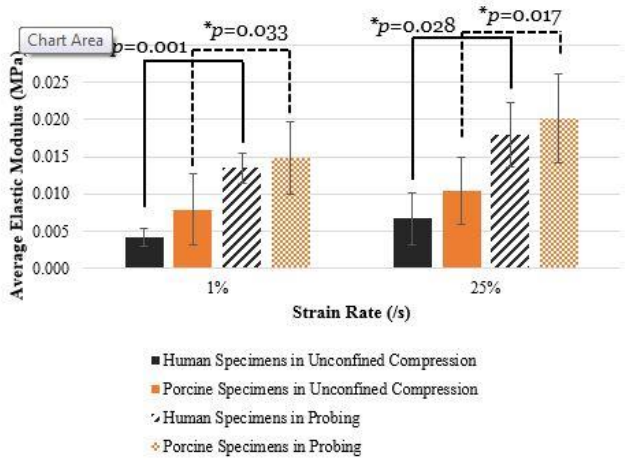

Fig. 4 Porcine human and porcine measured and modeled elastic modulus of the porcine specimens at different strain rates.

Both human and porcine elastic modulus of the spleen were observed to be strain rate dependent as expected due to the viscoelastic nature of this tissue. Strain rate was found to be a statistically significant factor (p=0.001) for the porcine specimens as an increase in stiffness was observed as the rate increased (Fig. 5). The post-hoc Tukey test revealed that the statistically significant increase in elastic modulus was observed only after the rate was above 100%/s (p<0.05). From the rates of 1%/s to 100%/s the elastic modulus only increased by 57%, but as the rate doubled from 500%/s to 1000%/s a 58% increase was observed (Fig. 5). A model (Eq 5) that was fit to the measured results with an R^2 of 0.98 was created to describe the relationship between the elastic modulus and strain rate. From Table 2 the b parameter shows how the elastic modulus changes with each percent strain increase in rate, while c parameter shows how this relationship changes as the rate increases. Through the modeled results (Fig. 5), it is seen that there is a slight inflection point at the rate of 100%/s. The rates of 100%/s and lower were statistically different than the rate of 500%/s (p<0.05).

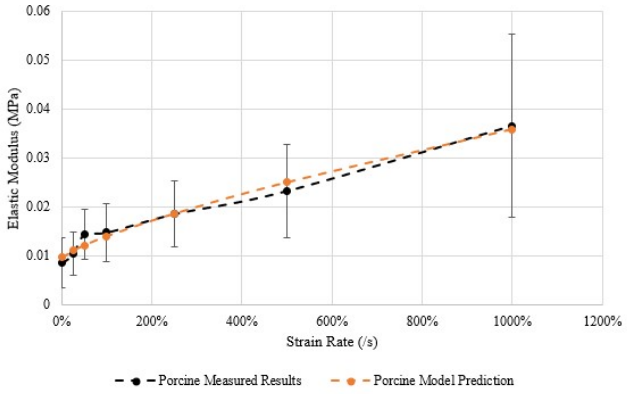

Fig. 5. Measured and modeled elastic modulus of the porcine specimens at different strain rates

Table 2. Values for the parameters of Eq. 5 for elastic modulus and failure strain properties

Variable	*a*	*b*	*c*	*ε̇*
Elastic Modulus	0.009	0.004	0.76	**Strain Rate**
Failure Strain	0.072	0.091	0.51	**Strain Rate**

B. Failure Properties

Failure stress of the porcine spleen was consistently higher than that of the human hosts (Fig. 6). Although only one human specimen was tested at each rate, both hosts exhibited strain rate dependent behavior with an increase in failure stress with each increase in strain rate. The factor of strain rate was statistically significant for the porcine organ (p=0.001). Similar to the elastic modulus results, only the failure stress at a rate of 500%/s was statistically different than at the other tested rates. The rate of 100%/s is also observed as an inflection point where the failure

stress relationship with strain rate changes slightly. The model fit of failure stress versus strain rate using Eq 5 showed that the parameter *c*, which determines the saturation level, was lower than the same parameter for the elastic modulus (Table 2).

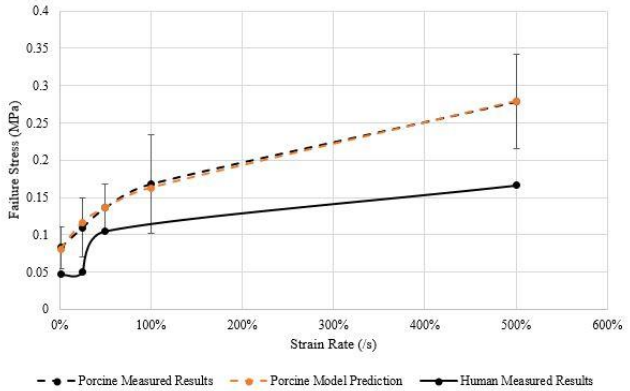

Fig. 6. Failure stress of human and porcine spleen at various rates under unconfined compression

No strain rate dependency was found for f failure strain (Fig. 7) for either the human or porcine specimens. Between the rates of 1%/s and 500%/s only a 6% increase in failure strain was observed and the failure strain at rates of 1%/s, 25%/s, and 50%/s were within 1% strain of each other on average. The ANOVA determined that the factor of strain rate was not statistically significant for failure strain ($p>0.05$).

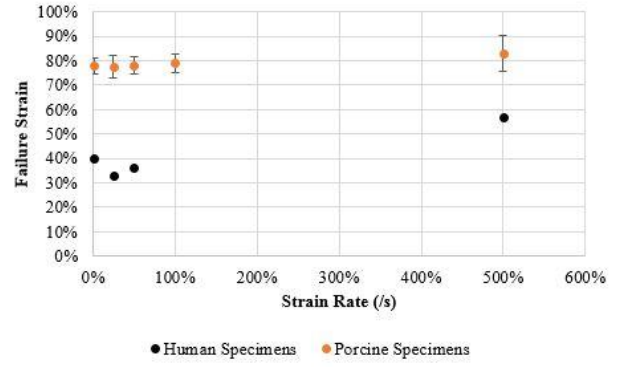

Fig. 7. Failure strain of porcine spleen at various rates under unconfined compression

IV. Discussion

Stress-strain curves and failure properties were experimentally determined using probing and unconfined compression protocols for human and porcine spleens. The elastic modulus of the porcine and human spleens was found to be similar at all loading rates for both testing protocols. However, porcine failure stress and strain were larger than the human spleen values. Previous studies used different protocols on portions of the spleen with varying failure results. Tamura (2002) tested rectangular sections of porcine spleens at rates up to 50%/s in compression and found failure stress and strain values similar to the current study [29]. Kemper (2012) performed tension testing on human spleen parenchyma and found failure strain approximately double that of porcine spleens (Uhere, 1995) as in the current study [21,26].

Other differences between hosts were additionally observed in the stress-strain curves. As seen in Fig. 3, the toe region of the porcine spleen is longer than that of the human spleen, with a smaller modulus. One possible reason for the differences between the two hosts is their relative age. The porcine hosts were within 2% of their average lifespan whereas the human host had reached the end of their natural life. Another contributor to the difference in results between specimens is that porcine spleens have thicker collagen walls and interwoven smooth muscle cells in the capsule which could result in the increase in failure strain [30-33]. Additionally, Suri (2017) found that the geometry of the spleen differs between species and Umarani (2018) found differences within the human population, which can affect the stress-strain behavior, particularly in the toe region before the tissue is fully engaged [34,35].

The current study used two different testing methodologies on the same specimens which resulted in different elastic moduli. The elastic modulus measured using the probing protocol was approximately twice that of the unconfined compression protocol for both hosts. This difference in modulus between protocols was hypothesized since the protocols activated different portions of the organs. In the probing condition a small area of the spleen was compressed but the resistance to the force still draws on the surrounding structure. In contrast, for unconfined compression testing the entire organ is being compressed at once. These results highlight the importance of using a testing protocol that emulates the expected in-vivo loading conditions when determining material properties for use in models.

The effect of strain rate on the elastic modulus is obvious, with modulus increasing with strain rate. The strain rate-elastic modulus relationship shows no sign of saturating, with modulus continuing to increase as strain rate increases. Failure stress was also observed to be strain rate dependent with an increase in failure stress with strain rate for both human and porcine tissue. The strain rate dependence continued through the largest rate tested with no apparent saturation. In contrast, strain rate was not observed to influence failure strain. Tamura (2002) also found a strain rate dependence for failure stress but not failure strain for porcine spleen parenchyma [29]. Thus, the spleen is sensitive to strain rate, even at higher rates, and when modeling dynamic loading this effect must be considered.

Testing whole intact spleens as was done in this study provides a unique insight into the overall mechanical behavior of the organ. Previous studies have investigated only the capsule or parenchyma in either tension or compression [19-25,28] however most do not provide results that are directly comparable to the current study. Stingl (2002) performed dynamic tension testing of the human spleen capsule and found the elastic modulus to be 10x the compression stiffness value obtained at every loading rate in the current study [19]. Umale (2013) performed a probing compression test on porcine spleens using a quasi-static rate and found the modulus to be slightly higher (7%) than the current

study porcine results for the quasi-static probing testing [24]. Additionally, Kemper (2012) found a difference between tension failure stress for porcine and human parenchyma sections of 150% as compared to the 68% found in the current study [20]. The difference in material properties between the previous and current studies highlights that effect that testing only a portion of the specimen (either via only the capsule for the tension tests or a small surface area for the probing test) may not accurately reflect the realities of blunt force trauma loading response.

Several limitations to this study exist. Due to constraints of the probing equipment only quasi-static and a single dynamic rate were probed, limiting the comparisons with the unconfined compression test results. Although standard protocols were used to handle the post-mortem tissue and monitor recovery after each test, the use of specimens for more than one non-destructive test has the potential to affect the results. In addition, the small number of human specimens that were available for testing indicates that a larger study may be required to verify the results.

V. Conclusion

The findings of this study reveal new information regarding material properties of intact human and porcine spleen in response to multiple strain rates as follows:

- Modulus and failure stress were found to be strain rate dependent while failure strain was independent of strain rate for both hosts. No saturation in strain rate effect was found for rates up to 500%/s.
- Elastic modulus measured using the probing protocol was larger than for unconfined compression in both hosts.
- At all loading rates porcine spleen elastic modulus was similar to human modulus while porcine failure stress and strain were higher than the human values.
- Difference in measured mechanical properties from tests of intact and partitioned organs indicate that values derived from intact organ tests should be used to develop computational or physical models of the spleen

These findings fill some knowledge gaps and allow for better understanding of the intact spleen response to various dynamic loading conditions, the feasibility of using porcine spleen properties as a substitute for human, and will aid in development of more accurate computational and physical models of the organ.

VI. Acknowledgements

The authors would like to thank the tissue donors for their precious gift to science. The funding for this study was provided by the department of defense grant #:4892-ARMY422 DHP-ELVIS Phase II.

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