Defence Research and Development Canada Recherche et développement pour la défense Canada

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# Material properties for numerical simulations for human, ballistic soap and gelatin

## High Level Technology Review

D.S. Cronin

Prepared by:

Cronin and Associates

Contract number: W7701-061933/001/QCL

Contract Scientific Authority: Amal Bouamoul, 418-844-4000 Ext. 4588

The scientific or technical validity of this Contract Report is entirely the responsibility of the contractor and the contents do not necessarily have the approval or endorsement of Defence R&D Canada.

**Defence R&D Canada – Valcartier**
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Author

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Duane S. Cronin

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# Abstract

The goal of this study was to undertake a literature survey and evaluate material properties for human tissues, and two widely used human tissue simulants (ballistic gelatin and ballistic soap) in support of future modeling efforts. Most biological and simulant materials display non-linear time-dependant response, and may be anisotropic. References containing mechanical properties for the relevant materials were identified and summarized in a tabular format, including applicable constitutive models where available. In some cases, multiple references were quoted to provide additional background or information on the models. The materials summarized in this study are those tissues within a typical area covered by a protective vest, and capture the primary tissues in the thorax, upper abdomen and upper extremity. Although complete mechanical data and constitutive models are not available for all tissues, sufficient data exists to provide a strong basis for future modeling efforts.

# Résumé

Le but de cette étude était d'entreprendre une enquête de littérature et d'évaluer les propriétés matérielles pour les tissus humains, et deux simulants humains employés couramment de tissu (gélatine balistique et savon balistique) à l'appui du futur modelant des efforts. La plupart des matériaux biologiques et de simulant montrent la réponse dépendant du temps non linéaire, et peuvent être anisotropes. Des références contenant les propriétés mécaniques pour les matériaux appropriés ont été identifiées et récapitulées dans un format tabulaire, y compris les modèles constitutifs applicables là où disponibles. Dans certains cas, des références multiples ont été citées pour fournir le fond ou les informations additionnelles sur les modèles. Les matériaux récapitulés dans cette étude sont ces tissus dans un domaine typique couvert par un gilet protecteur, et capturent les tissus primaires dans le thorax, l'abdomen supérieur et l'extrémité supérieure. Bien que les données mécaniques complètes et les modèles constitutifs ne soient pas disponibles pour tous les tissus, les données suffisantes existent pour fournir une base forte pour le futur modelant des efforts.

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# 1. Introduction

The goal of this study was to review existing material properties for human tissues (hard and soft) and two common soft tissue stimulants (ballistic gelatin and ballistic soap) for the purpose of future hydrocode numerical modeling. This study was undertaken in support of the Soldier Integrated Precision Effects System Technology Demonstration Program (SIPES) program [Bouamoul, 2008].

## 1.1 Background

Literature sources used in this review included relevant journals, text books and conference proceedings. Often, several references describing different aspects of mechanical response were available for a given tissue and the relevant properties were taken from each of these references. It is well-known that biological tissues exhibit a large degree of variability in terms of mechanical properties which may depend on age, gender, level of physical activity and other factors [Fung, 1993].

When considering hard tissues, properties for the constituent materials (cortical and cancellous bone) are provided. Given that many of the hard tissues have different composition in terms of cortical bone shell thickness and cancellous bone density, experimental data for the specific components was also included where available. It should be noted that bone density and physical dimensions are subject-specific, and should be considered when developing future numerical models. Further, many existing models use lumped parameters that account for the response of cortical and cancellous bone through equivalent properties, where the equivalent properties depend to some extent on the mode of loading and goal of the model. Although this is common practice and computationally efficient, caution should be exercised in terms of extending this approach to other modeling scenarios for which the original model was not validated.

The scope of this review, in terms of the materials considered, was discussed at meetings with the Scientific Authority. The current study is primarily concerned with materials in the typical protective vest coverage area including the torso, upper extremity and upper abdomen. This is shown schematically in Figure 1 [NLM, 2008]. The biomaterials investigated include:

Hard tissues (rib and sternum, clavicle, humerus)
Lungs
Heart
Skin/vessels/muscle
Upper abdominal organs
Spine

Material properties can generally be classified based on constitutive response. When considering biomaterials or simulants, there are 3 general classes or approaches that are commonly used:

- Elastic (linear, hyperelastic)
- Viscoelastic (linear, non-linear)
- Elastic-Plastic, including rate effects

In addition, many materials such as bone may exhibit anisotropy. Although a complete constitutive model addressing all aspects of the material is attractive, it is often appropriate to consider a simpler version for practical reasons such as available data and expected loading conditions. Further, it is desirable to work with existing constitutive models that have already been implemented into the numerical codes being considered since the development time and cost can be significant for these models, and often a complete set of material test data is not available to fully describe the constitutive behaviour in all aspects. In general, we seek to identify and use a constitutive model that is available, and includes the important aspects of material response for the given problem.

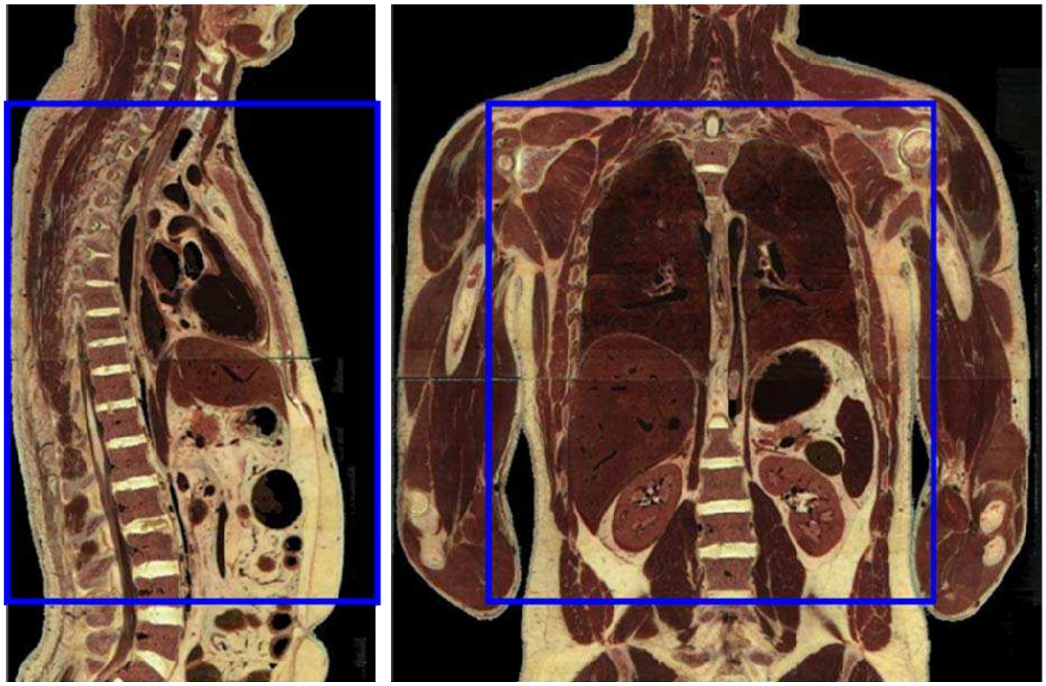


***Figure 1. Sagittal [L] and Coronal[R] views of a 50$^{th}$ percentile male [NLM 2008], indicating the focus area for the study***

# 2. Material Properties Review

The material properties review is divided into bone or hard tissues and soft tissues. For the hard tissues, the mechanical properties of the constituent materials (cortical and cancellous bone) are provided since future high-resolution models could represent these individual components and the associated material properties. Where available, mechanical properties for the actual full bones are also presented, which can be used to validate a lumped property approach in coarser models, or to validate high-resolution models.

## 2.1 Hard Tissues

### 2.1.1 Cortical bone

Cortical bone refers to the high density bone present in the long bones of the body (the humerus for example), and as a thin shell around the ribs, sternum and clavicle considered in this study. This section provides a general overview of cortical bone and the associated mechanical properties. Cortical bone typically exhibits relatively brittle behaviour and a corresponding low strain to failure, anisotropy, and dependence on strain rate. A modest amount of post-yield deformation (Figure 2) is often observed, and typically included in numerical simulations to enhance model stability. The mechanical properties are known to vary with location, function and orientation within the bone (Figure 3), as well as between various bones. Density variations of 1850-2000 kg/m$^3$ [Cowin 1889] are also common. The elastic constants for cortical bone have been reported by Cowin as shown in Table 1. Several studies have been undertaken to evaluate the strain rate dependence of cortical bone. Figure 4 shows the data from McElhaney [McElhaney 1966]. More recently, studies have investigated high-rate properties of bovine bone [Ferreira, 2006] but with some non-intuitive results, such as decreasing modulus with increasing strain rate. This is not supported by more recent work [Hansen 2008] where the modulus was found to increase with increasing rate, albeit across a narrower range of strain rates (up to approximately 30 s$^{-1}$). For this reason, the data presented by McElhaney is recommended.

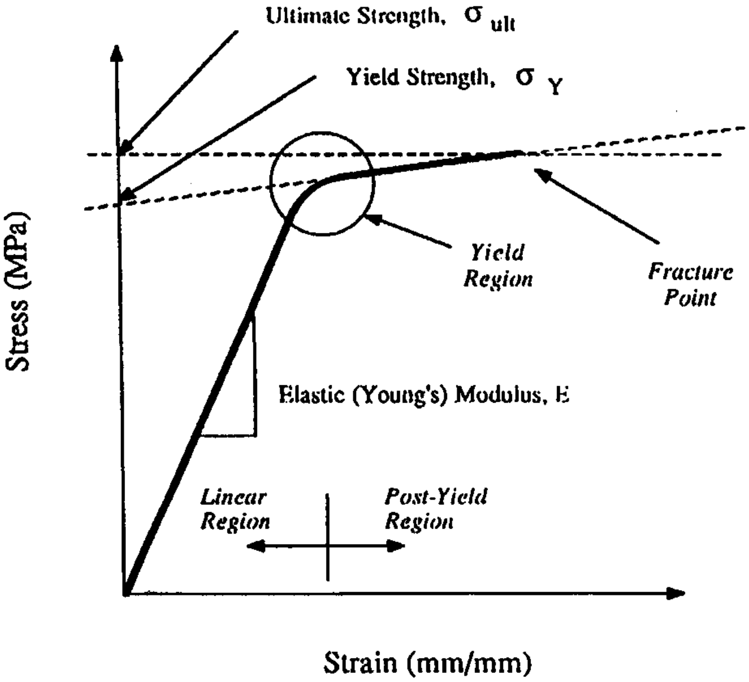


*Figure 2. Cortical bone mechanical properties [Nahum 2002]*

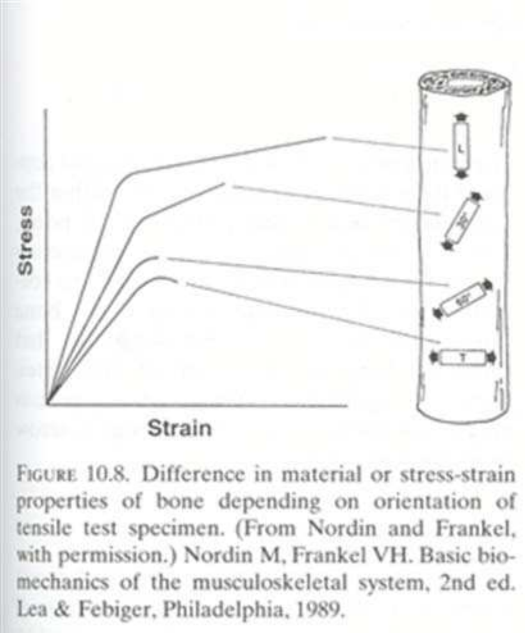
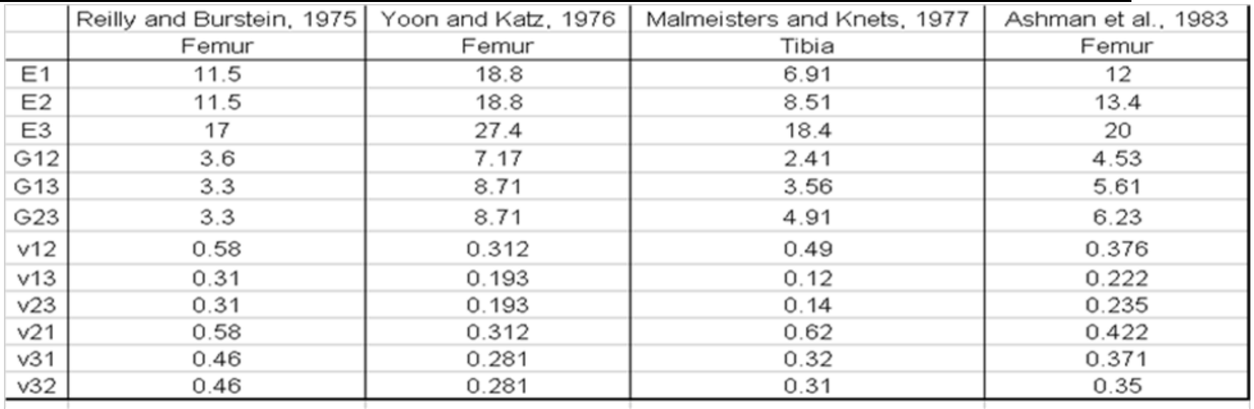


FIGURE 10.8. Difference in material or stress-strain properties of bone depending on orientation of tensile test specimen. (From Nordin and Frankel, with permission.) Nordin M, Frankel VH. Basic biomechanics of the musculoskeletal system, 2nd ed. Lea & Febiger, Philadelphia, 1989.

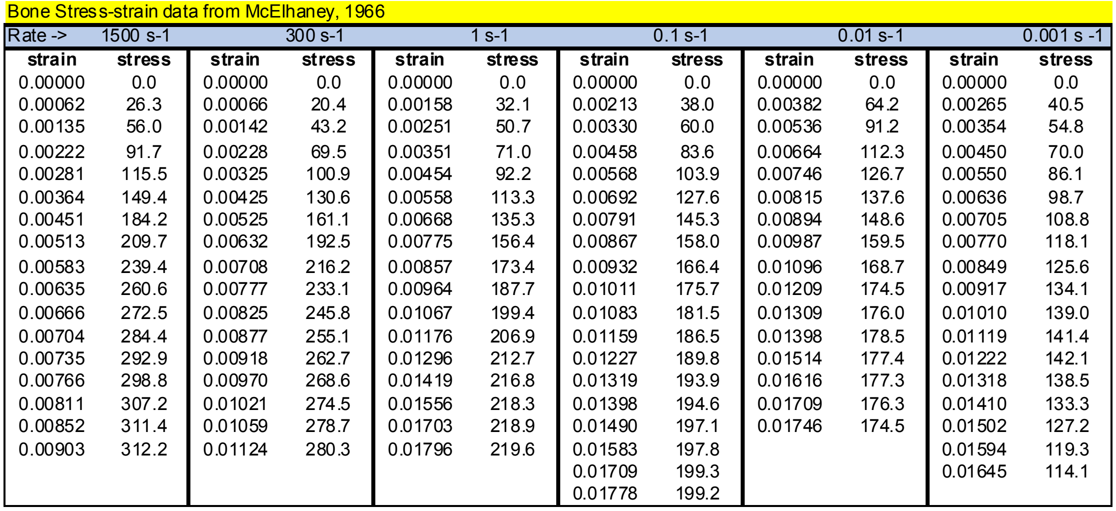
*Figure 3. Cortical bone mechanical properties as a function of orientation [Nahum 2002]*

***Table 1. Elastic constants for cortical bone [Cowin 1989]***



| | Reilly and Burstein, 1975 | Yoon and Katz, 1976 | Malmeisters and Knets, 1977 | Ashman et al., 1983 |
|---|---|---|---|---|
| | Femur | Femur | Tibia | Femur |
| E1 | 11.5 | 18.8 | 6.91 | 12 |
| E2 | 11.5 | 18.8 | 8.51 | 13.4 |
| E3 | 17 | 27.4 | 18.4 | 20 |
| G12 | 3.6 | 7.17 | 2.41 | 4.53 |
| G13 | 3.3 | 8.71 | 3.56 | 5.61 |
| G23 | 3.3 | 8.71 | 4.91 | 6.23 |
| v12 | 0.58 | 0.312 | 0.49 | 0.376 |
| v13 | 0.31 | 0.193 | 0.12 | 0.222 |
| v23 | 0.31 | 0.193 | 0.14 | 0.235 |
| v21 | 0.58 | 0.312 | 0.62 | 0.422 |
| v31 | 0.46 | 0.281 | 0.32 | 0.371 |
| v32 | 0.46 | 0.281 | 0.31 | 0.35 |

***Table 2. Cortical bone properties – High strain rate data [McElhaney 1966] (ref. Figure 4)***



Bone Stress-strain data from McElhaney, 1966

| Rate -> 1500 s-1 | | 300 s-1 | | 1 s-1 | | 0.1 s-1 | | 0.01 s-1 | | 0.001 s -1 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **strain** | **stress** | **strain** | **stress** | **strain** | **stress** | **strain** | **stress** | **strain** | **stress** | **strain** | **stress** |
| 0.00000 | 0.0 | 0.00000 | 0.0 | 0.00000 | 0.0 | 0.00000 | 0.0 | 0.00000 | 0.0 | 0.00000 | 0.0 |
| 0.00062 | 26.3 | 0.00066 | 20.4 | 0.00158 | 32.1 | 0.00213 | 38.0 | 0.00382 | 64.2 | 0.00265 | 40.5 |
| 0.00135 | 56.0 | 0.00142 | 43.2 | 0.00251 | 50.7 | 0.00330 | 60.0 | 0.00536 | 91.2 | 0.00354 | 54.8 |
| 0.00222 | 91.7 | 0.00228 | 69.5 | 0.00351 | 71.0 | 0.00458 | 83.6 | 0.00664 | 112.3 | 0.00450 | 70.0 |
| 0.00281 | 115.5 | 0.00325 | 100.9 | 0.00454 | 92.2 | 0.00568 | 103.9 | 0.00746 | 126.7 | 0.00550 | 86.1 |
| 0.00364 | 149.4 | 0.00425 | 130.6 | 0.00558 | 113.3 | 0.00692 | 127.6 | 0.00815 | 137.6 | 0.00636 | 98.7 |
| 0.00451 | 184.2 | 0.00525 | 161.1 | 0.00668 | 135.3 | 0.00791 | 145.3 | 0.00894 | 148.6 | 0.00705 | 108.8 |
| 0.00513 | 209.7 | 0.00632 | 192.5 | 0.00775 | 156.4 | 0.00867 | 158.0 | 0.00987 | 159.5 | 0.00770 | 118.1 |
| 0.00583 | 239.4 | 0.00708 | 216.2 | 0.00857 | 173.4 | 0.00932 | 166.4 | 0.01096 | 168.7 | 0.00849 | 125.6 |
| 0.00635 | 260.6 | 0.00777 | 233.1 | 0.00964 | 187.7 | 0.01011 | 175.7 | 0.01209 | 174.5 | 0.00917 | 134.1 |
| 0.00666 | 272.5 | 0.00825 | 245.8 | 0.01067 | 199.4 | 0.01083 | 181.5 | 0.01309 | 176.0 | 0.01010 | 139.0 |
| 0.00704 | 284.4 | 0.00877 | 255.1 | 0.01176 | 206.9 | 0.01159 | 186.5 | 0.01398 | 178.5 | 0.01119 | 141.4 |
| 0.00735 | 292.9 | 0.00918 | 262.7 | 0.01296 | 212.7 | 0.01227 | 189.8 | 0.01514 | 177.4 | 0.01222 | 142.1 |
| 0.00766 | 298.8 | 0.00970 | 268.6 | 0.01419 | 216.8 | 0.01319 | 193.9 | 0.01616 | 177.3 | 0.01318 | 138.5 |
| 0.00811 | 307.2 | 0.01021 | 274.5 | 0.01556 | 218.3 | 0.01398 | 194.6 | 0.01709 | 176.3 | 0.01410 | 133.3 |
| 0.00852 | 311.4 | 0.01059 | 278.7 | 0.01703 | 218.9 | 0.01490 | 197.1 | 0.01746 | 174.5 | 0.01502 | 127.2 |
| 0.00903 | 312.2 | 0.01124 | 280.3 | 0.01796 | 219.6 | 0.01583 | 197.8 | | | 0.01594 | 119.3 |
| | | | | | | 0.01709 | 199.3 | | | 0.01645 | 114.1 |
| | | | | | | 0.01778 | 199.2 | | | | |

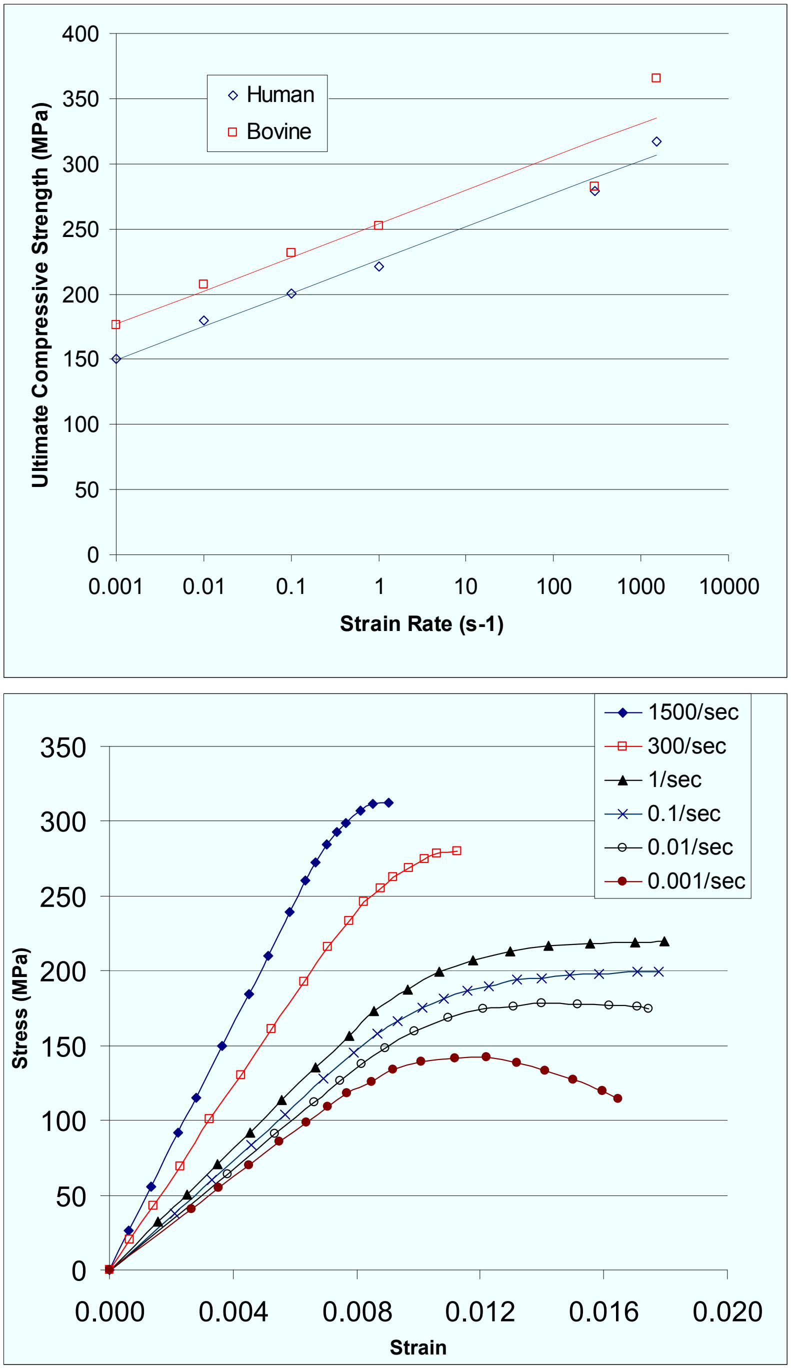


***Figure 4. Cortical bone strain rate dependence [adapted from McElhaney 1966]***

### 2.1.2 Cancellous bone

Cancellous (trabecular or spongy) bone is present in every bone in the body as an open network of bone plates (trabeculae). For the bones considered in this study, it occurs within a thin cortical shell, where the density of the cancellous bone may vary from 150-1000 kg/m$^3$ [Cowin 1989]. The mechanical properties of cancellous bone can be related to the bone density as shown in Figure 5 [Nahum 2002], which varies depending on body region and function.

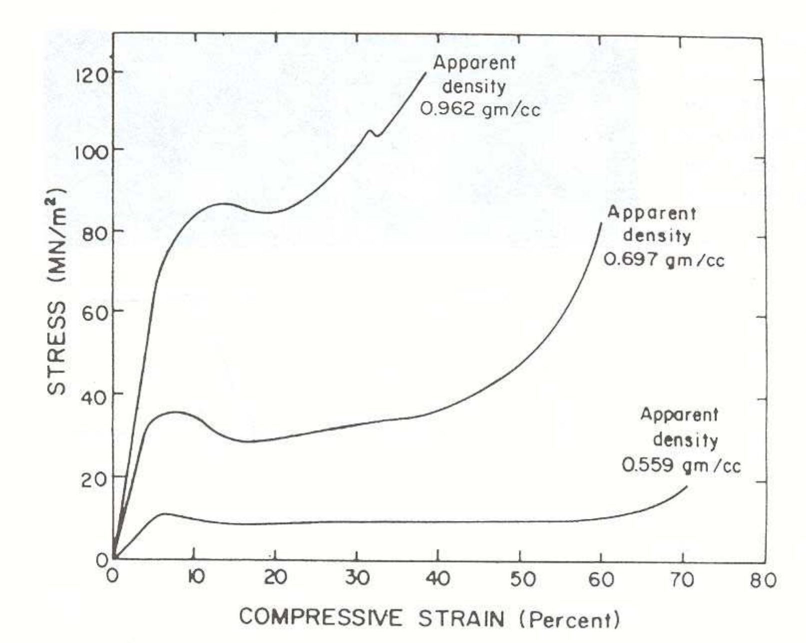


***Figure 5. Cancellous bone mechanical properties [Nahum, 2002]***

The modulus and ultimate compressive strength of this bone can also be expressed as a function of density and strain rate [Cowin 1989] as shown in Equations 1 and 2, respectively. However, it should be noted that these relationships were developed for strain rates from 0.001 to 10 1/s and may not be applicable at higher strain rates.

$$E = 3790\dot{\varepsilon}^{0.06}\rho^{3} \qquad (1)$$

$$\sigma_{UCS} = 68\dot{\varepsilon}^{0.06}\rho^{2} \qquad (2)$$

### 2.1.3 Humerus

The humerus is a long bone located in the upper extremity (Figure 6). The properties presented below (Table 3) are for the cortical bone (shaft or diaphysis) in the humerus.

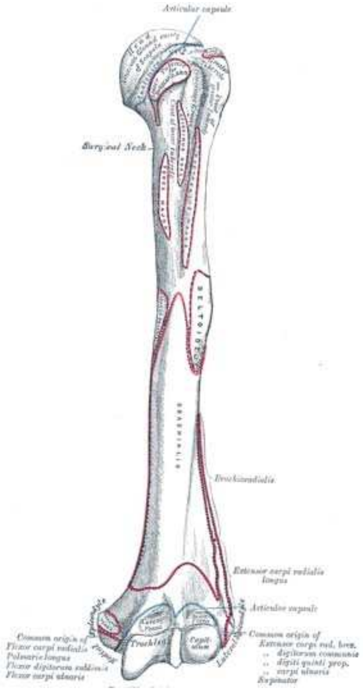


*Figure 6. Humerus Bone [Grays 1918]*

***Table 3. Cortical bone properties for the humerus***

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Constitutive law: Elastic Anisotropic | | | | | | | | | | | | | | |
| | | Density (kg/m^3) | | | Modulus (GPa) | | | | | | Poisson's Ratio | | | |
| | | | E1 (GPa) | E2 (GPa) | E3 (GPa) | G12 (GPa) | G13 (GPa) | G23 (GPa) | v12 | v13 | v23 | v21 | v31 | v32 |
| Cowin, 1989 | Cortical bone elastic constants | 2000 | 11.5 | 11.5 | 17 | 3.6 | 3.3 | 3.3 | 0.58 | 0.31 | 0.31 | 0.58 | 0.46 | 0.46 |
| | (Human Femur) | | 1-direction - Through Thickness | | | | | | | | | | | |
| | | | 2-direction - Transverse | | | | | | | | | | | |
| | | | 3-direction - Longitudinal | | | | | | | | | | | |
| | | | Compressive Breaking Load (kg) | | | Torsional Breaking Moment (kg/cm) | | | | | | | | |
| Nahum 2002 | Strength Properties (static) | | 2580 | | | 606 | | | | | | | | |
| | | | | | | | | | | | | | | |
| Constitutive law: Elastic-Plastic with Strain Rate Effects | | | | | | | | | | | | | | |
| McElhaney, 1966 | Strain rate effects | | **See Figure 4** | | | | | | | | | | | |
| | Plastic properties, failure strength (dynamic) | | | | | | | | | | | | | |

Additional References:
Duma 1998

### 2.1.4 Ribs

The ribs are composed of a cortical bone shell (typically less than 1mm in thickness) and a cancellous bone core (Figure 7). The cortical shell varies in density around the circumference of the bone, and along the length of each rib. The recommended mechanical properties for the ribs are presented in Table 4, based on tensile tests and bending tests.

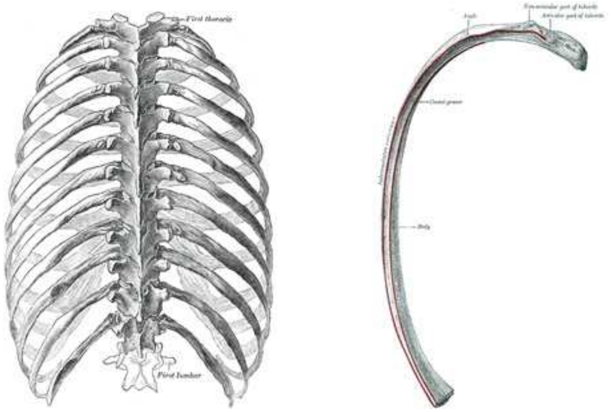


*Figure 7. Rib – Rear view of thoracic cage [L] and central rib of the left side [R] [Gray 1918]*

*Table 4. Material properties for the ribs (recommended properties in bold)*

| Constitutive law: Elastic-Plastic | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Reference | Mode | Rate | Size | | Density (kg/m^3) | Modulus (GPa) | Yield Strength (MPa) | Ultimate Strength (MPa) | Ultimate Strain (%) |
| Kemper 2005 | Tensile | Quasi-static | Tensile coupon | PHMS | | **13.9** | **93.9** | **124.2** | **2.71** |
| Greer 2006 | | | | | **1561** | | | | |
| Charpail 2005 | FE Model parameters | Quasi-static | Full rib | PHMS | 2000 | 13 | 150 | 150 | 10 |
| | | | | | 1000 | 2.4 | 2 | 2.2 | 10 |
| | | | | | Mean Rupture Load (N) | | Mean Displacement (mm) | | |
| Charpail 2005 | Bending | | Full rib | PHMS | 87 | | 41 | | |

Additional References:
Yoganandan 1998

### 2.1.5 Sternum

The sternum is a flat bone (Figure 8), supporting the clavicle and connected to the ribs. It consists of the manubrium, body, and xiphoid process. The sternum consists of cancellous bone with a thin cortical shell. Detailed mechanical properties were not available at the time of this study and it is recommended to use properties similar to those for the ribs (Table 5), based on the properties of the constituent matierals.

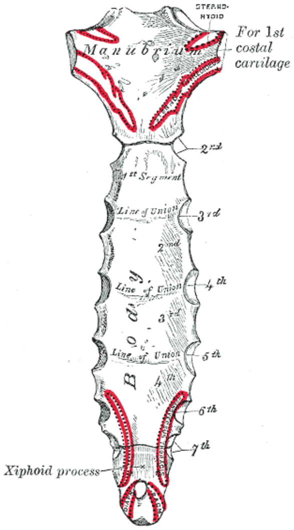


*Figure 8. Sternum [Gray 1918]*

***Table 5. Material properties for the sternum***

| Constitutive law: Elastic-Plastic | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Reference | Mode | Rate | Size | | Density (kg/m^3) | Modulus (GPa) | Poisson's Ratio (-) | Fracture Force (kN) |
| Bass 2004 | BABT impact | Dynamic | Full body | PMHS | | | | 25 |
| Greer 2006 | | | | | 1354 | 3.51 | 0.387 | |

### 2.1.6 Clavicle

The clavicle is a flat bone (Figure 9), doubly curved in shape, and composed of a cortical shell with a cancellous bone core. Available mechanical properties include cortical shell and cancellous bone materials (Table 6) based on a numerical model developed by Dupre [2007].

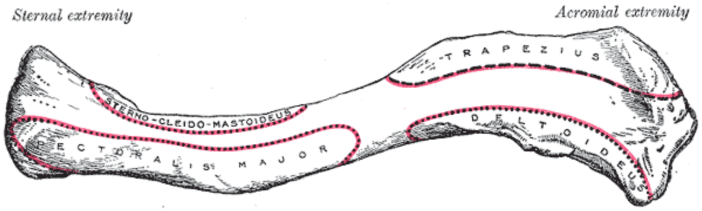


***Figure 9. Clavicle [Gray 1918]***

***Table 6. Material properties for the clavicle***

Constitutive law: Elastic-Plastic

| Reference | Size | Density (kg/m^3) | Modulus (GPa) | Poisson's U Ratio (-) | ltimate Strength (MPa) | Ultimate Strain (%) |
|---|---|---|---|---|---|---|
| Dupre 2007 | Cortical Shell | 1850 | 11.0 | 0.3 | 120 | 3.0 |
| Dupre 2007 | Cancellous Bone | 1000 | 0.5 | 0.1 | 4 | 1.5 |

## 2.2 Soft Tissues

### 2.2.1 Costal Cartilage

The costal cartilage connects the ribs to the sternum (Figure 10). The presented material properties are based on indentation (low rate) tests (Table 7).

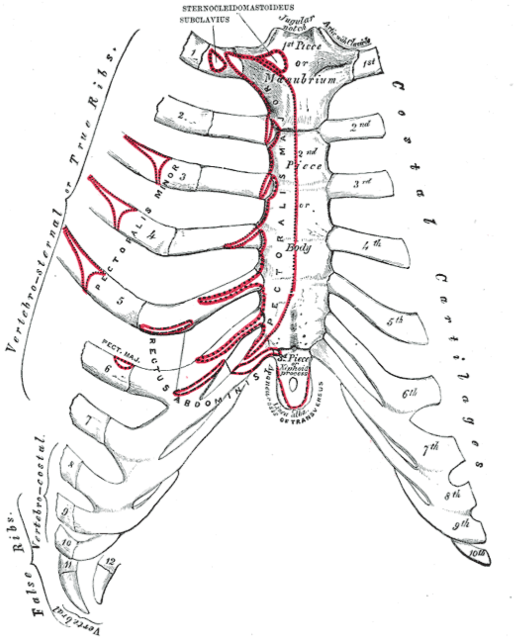


*Figure 10. Costal cartilage [Gray 1918]*

*Table 7. Material properties for costal cartilage*

| Constitutive law: Linear Viscoelastic | | | | | | | |
|---|---|---|---|---|---|---|---|
| Reference | Mode | Rate | Size | | Density | Modulus | Poissons Ratio |
| | | | | | (kg/m^3) | (MPa) | (-) |
| Lau 2008 | Indentation | Relaxation | Local properties | PMHS | | 5.3 | |
| Greer 2006 | | | | | 1203 | | 0.4 |
| | | | | | | G0 (kPa) | G infinity (kPa) |
| Mattice 2006 | Indentation | Relaxation | Local properties | Porcine | | 8 | 1.8 |

### 2.2.2 Lungs

The lungs are located within the thoracic cage, surrounding the heart (Figure 11). The mechanical properties are commonly expressed using a strain energy relationship originally proposed by Vawter (Equation 3) (Table 8).

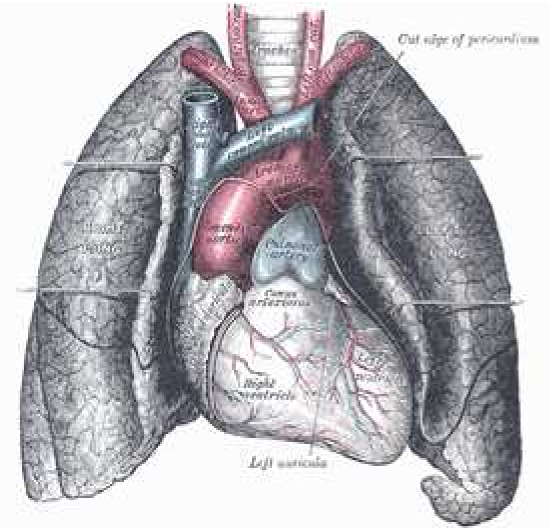


*Figure 11. Front view of lungs and heart [Gray 1918]*

*Table 8. Material properties for lung tissue*

| Strain Energy Function (Vawter 1980) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Density | K | C/Delta | Alpha | Beta | C1/Delta | C2 |
| | (kg/m^3) | (kPa) | (kPa) | (-) | (-) | (kPa) | (-) |
| Yuen 2008 | 200 | 24500 | 0.592 | 5.85 | -3.21 | 0.0193 | 2.71 |

Additional References:
Vawter 1980
Saraf 2006
Jahed 1989

$$W = \frac{C}{2\Delta}\exp(\alpha I_1^2 + \beta I_2) + \frac{12C_1}{\Delta(1+C_2)}[A^{(1+C_2)} - 1]$$

$$A^2 = \frac{4}{3}(I_1 + I_2) - 1$$

$$I_1 = e_{11} + e_{22} + e_{33}$$

$$I_2 = e_{11}e_{22} + e_{22}e_{33} + e_{33}e_{11} - e_{12}^2 - e_{23}^2 - e_{31}^2$$

(3)

### 2.2.3 Heart

The heart is located in the thoracic cavity, between the lungs (Figure 11). The material properties for the heart tissue are often expressed using a strain energy function, shown in Table 9 and Equation 4.

*Table 9. Material properties for the heart*

| Strain Energy Function (Vawter 1980) | | | | | |
|---|---|---|---|---|---|
| | Density (kg/m^3) | Strain Rate (1/s) | K (GPa) | Strain Rate (1/s) | G (kPa) |
| Greer 2006 | 1030 | | | | |
| Saraf 2006 | | 300 | 0.49 | 200 | 60 |
| | | 1200 | 0.25 | 2800 | 148 |
| | | C (kPa) | bf | bt | bfs |
| Guccione 1995 | | 0.876 | 18.48 | 3.58 | 1.627 |

Additional References:
Guccione 1991
Blemker 2005

$$W = \frac{C}{2}(e^{Q} - 1) \quad \text{and} \quad E_{\alpha\beta} = \frac{1}{2}\left(\frac{\partial x^k}{\partial v^\alpha}\frac{\partial x^k}{\partial v^\beta} - \delta_{\alpha\beta}\right)$$

where

$$\begin{aligned} Q = {} & b_f E_{11}^2 + b_t(E_{22}^2 + E_{33}^2 + E_{23}^2 + E_{32}^2) \\ & + b_{fs}(E_{12}^2 + E_{21}^2 + E_{13}^2 + E_{31}^2), \end{aligned} \tag{4}$$

### 2.2.4 Vessels, Skin and Muscle

The mechanical properties for arteries, skin and muscle tissues are presented below in Table 10 with Equation 5, Table 11, and Table 12 with Figure 12, respectively.

*Table 10. Artery material properties*

| Artery: Hyperelastic Material | | | | | | |
|---|---|---|---|---|---|---|
| | Density (kg/m^3) | C10 (kPa) | C01 (kPa) | C11 (kPa) | C20 (kPa) | C30 (kPa) |
| Prendergast 2003 | 1000 | 18.9 | 2.75 | 857.18 | 590.42 | 0 |

Additional References:
Lally 2005

$$W = \sum_{i=0, j=0}^{\infty} a_{ij}(I_1 - 3)^{m}(I_2 - 3),^{n}a_{00} = 0, \qquad (5)$$

*Table 11. Skin material properties*

| Skin: Elastic | | | |
|---|---|---|---|
| | Density (kg/m^3) | E (MPa) | Poisson`s Ratio |
| Dupre 2007 | 1000 | 1.5 | 0.46 |

Additional References:
Reihsner 1995
Ferguson 1981
Martin 1988

***Table 12. Muscle material properties***

| Muscle: Rate dependant load curves | | | | |
|---|---|---|---|---|
| | Density (kg/m^3) | K (GPa) | mu (Damping) | Stress-strain response |
| Forbes 2005 | 1040 | 2.48 | 0.1 | Specified as load curves |

Additional References:
VanSligtenhorst 2006
VanSligtenhorst 2004
Chawla 2006
Van Loocke 2008

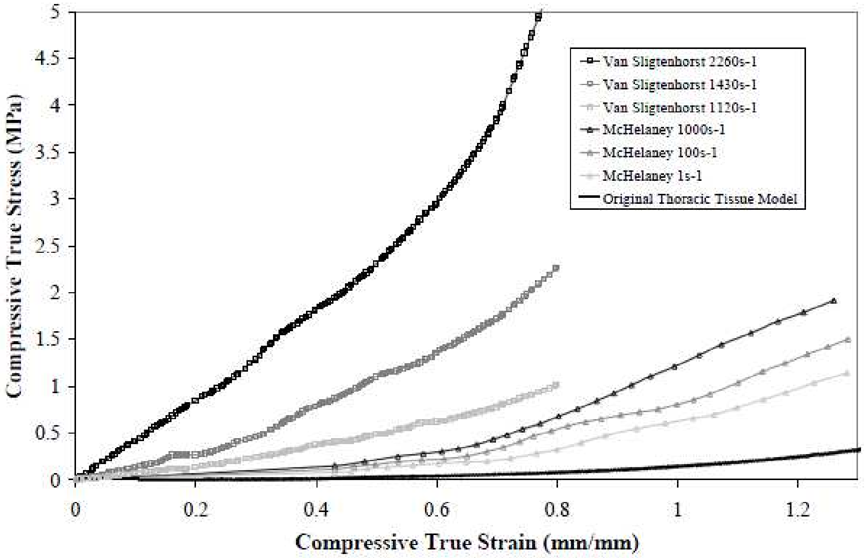


***Figure 12. Compressive properties for muscle tissue [Forbes 2005]***

### 2.2.5 Abdominal organs

The upper abdominal organs include the liver stomach and spleen (Figure 13), with the associated mechanical properties reported in Table 13 and Equation 6.

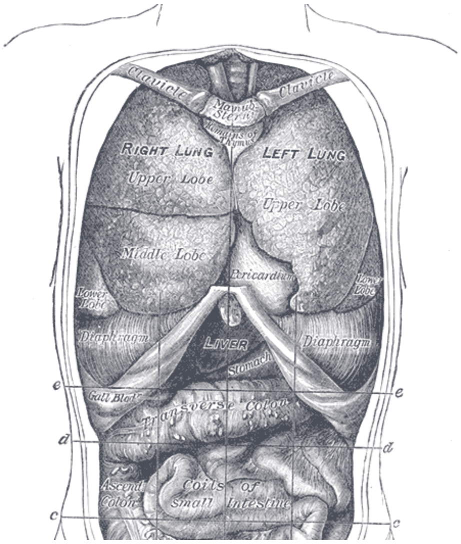


*Figure 13. Abdominal organs [Gray 1918]*

*Table 13. Material properties for abdominal organs*

| Strain Rate Dependant Properties | | | | | | |
|---|---|---|---|---|---|---|
| | | Density (kg/m^3) | Strain Rate (1/s) | K (GPa) | Strain Rate (1/s) | G (kPa) |
| Saraf 2006 | Liver | | 400 | 0.28 | 280 | 37 |
| | | | 1000 | 0.28 | 1800 | 340 |
| Saraf 2006 | Stomach | | 350 | 0.48 | 300 | 8 |
| | | | 2900 | 0.48 | 2200 | 45 |

| Nonlinear Elastic Properties | | | | | |
|---|---|---|---|---|---|
| | | Density (kg/m^3) | Beta (Pa) | Alpha (-) | Gamma (Pa) |
| Rosen 2008 | Liver | 1040 | 7377.1 | 20.63 | 3289.4 |
| | Stomach | 1040 | 4934.9 | 21.51 | 11,105.90 |
| | Spleen | 1040 | 3364.4 | 12.94 | 19,853.10 |

Additional References:
Mattice 2006
Farshad 1999
Shi 2008

$$\sigma = \beta(e^{\alpha\epsilon^2} - 1) + \gamma\epsilon \qquad (6)$$

### 2.2.6 Spinal Cord

***Table 14. Material properties for the spinal cord***

| Relaxation model | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | G0 | G1 | v1 | G2 | v2 | G3 | v3 | Beta |
| Fiford 2005 | 0.0288 | 21.219 | 0.7913 | 0.019 | 0.7103 | 0.08902 | 0.02155 | 0.10065 | 0.00266 | 1.34182 |

Additional References:
Hung 1981

$$Y(\varepsilon, t) = \sigma^e(\varepsilon)^* G(\varepsilon, t)$$

$$\sigma^e(\varepsilon) = A(\mathrm{e}^{B\varepsilon} - 1)$$

$$G(\varepsilon, t) = G_0 + (1 + \beta\dot{\varepsilon})\left\lfloor G_1 \mathrm{e}^{-v_1 t} + G_2 \mathrm{e}^{-v_2 t} + G_3 \mathrm{e}^{-v_3 t} \right\rfloor \tag{7}$$

## 2.3 Tissue Simulants

### 2.3.1 Ballistic Gelatin

Ballistic gelatin is widely used as a tissue simulant, commonly in the 10%, 4C and 20%, 10C formulations. The mechanical properties are presented in Table 15, with the corresponding stress-strain curves in Figures 14 (10%) and 15 (20%).

*Table 15. Material properties for ballistic gelatin*

| Stress-Strain Curves | | |
|---|---|---|
| | Density (kg/m^3) | |
| Sellier 1994 | 1060 | |
| Salisbury 2008 | | Stress-strain data (10%, 4C Gelatin) |
| Salisbury 2008 | | Stress-strain data (20%, 10C Gelatin) |

Additional References:
Caillou 1994
Jussila 2004
van Bree 1998
VanSligtenhorst 2004
Fackler 1987
Jussila 2005

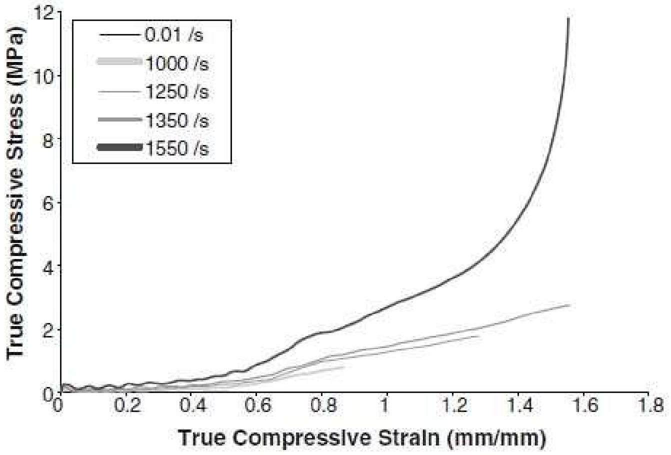


*Figure 14. Compressive properties for 10% ballistic gelatin [Salisbury 2008]*

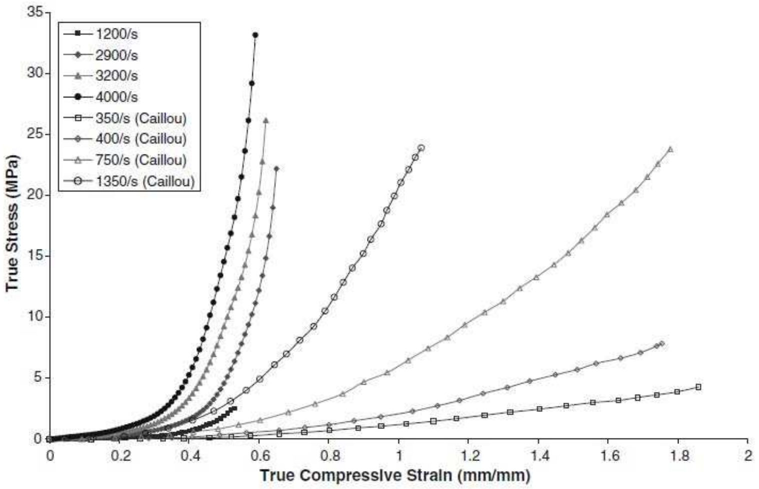


*Figure 15. Compressive properties for 20% ballistic gelatin [Salisbury 2008]*

### 2.3.2 Ballistic Soap

Ballistic soap is used as a tissue simulant, and exhibits elastic-plastic. The mechanical properties are presented in Table 16, with the corresponding constitutive model shown in Equation 8.

*Table 16. Material properties for ballistic soap*

| Johnson Cook Model | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Density (kg/m^3) | E (MPa) | A (MPa) | B | C | D | K (GPa) |
| Sellier 1994 | 1060 | | | | | | |
| Ndompetelo 2006 | | 21.45 | 1.64 | 6.86 | 1.73 | 0.0346 | 3.00 |

Additional Refences:
Nsiampa, 2008

$$\sigma = (A + B\varepsilon_p^C)(1 + D\ln(\dot{\varepsilon}_p)) \qquad (8)$$

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The goal of this study was to undertake a literature survey and evaluate material properties for human tissues, and two widely used human tissue simulants (ballistic gelatin and ballistic soap) in support of future modeling efforts. Most biological and simulant materials display non-linear time-dependant response, and may be anisotropic. References containing mechanical properties for the relevant materials were identified and summarized in a tabular format, including applicable constitutive models where available. In some cases, multiple references were quoted to provide additional background or information on the models. The materials summarized in this study are those tissues within a typical area covered by a protective vest, and capture the primary tissues in the thorax, upper abdomen and upper extremity. Although complete mechanical data and constitutive models are not available for all tissues, sufficient data exists to provide a strong basis for future modeling efforts.

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