Review of Mechanical Properties of Human Body Soft Tissues in the Head, neck and spine

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ABSTRACT

In this paper we review the mechanical properties of soft tissues available in literature. Human body regions are split into different parts to pursue this study. This review paper focuses on the soft tissues in the head, neck and spine. The tissues studied include brain tissues, scalp tissues, ligaments in cervical spine, neck muscles and spinal soft tissues. Material properties, which are directly extracted from the experimental methods, and the constitutive properties that have been used in finite element models are looked at. Isolated tissue tests, sub-segmental tests and full-scale tests used for validating the respective finite element models are investigated. Static and dynamic properties are sorted according to the tissue type. Variations in the data from different sources has been studied and summarized. Scatter in the static properties and less frequently available dynamic properties indicate the need for further testing and alternate material models.

Keywords: Material properties, Human soft tissues, Head, Neck, Spine

INTRODUCTION

Human body finite element (FE) models, if based on a realistic geometry and bio-fidelic material properties, can be useful in designing safer vehicles in order to reduce incidences of injuries and fatalities in road crashes[1,2]. To identify the reliability and variations within the material properties reported in literature, a review of the properties of soft tissue in the human body has been conducted. Human body regions are divided into three parts a) Lower extremities b) Head, neck and spine c) Upper extremity, chest and abdomen. The present study reviews the properties of the soft tissues in head, neck and spine region. Constitutive properties of soft tissues used in the finite element models and the validating experimental procedures are also reviewed. Mechanical properties are categorized in the following sections according to major tissue type in the respective body regions. Variations in reported properties have been used to identify issues which still need to be addressed.

HEAD

Head injuries are the most common injuries with Abbreviated Injury Scale (AIS) >=2 for belted occupants in automotive frontal impacts[3,4] and the second leading cause of injuries (after lower extremities) having AIS between 2 and 6 in pedestrian accidents[5]. Head injuries may cause either a temporary or a permanent damage to parts of the head and can be life threatening. These injuriescan be grouped as those causing scalp damage, skull fracture, brain injury, or a combination of these[6]. Anatomy of the head is mainly divided into two parts a) *face*, which represents the front part of the head and b) *head* which comprises the center and rear part of the head[7]. Soft tissues in the face include skin, muscles, tongue, cartilage and ligaments. Studies related to facial soft tissues are scarce due to its low load sharing capability and mostly have a low severity. They therefore have been excluded

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from this study. Soft tissues in the head are mainly present in the scalp, meninges and brain regions. Scalp consists of skin, connective tissue, aponerosis, loose connective tissue, periosteum. Meninges region which separate the brain and the spinal cord from the surrounding bones consists of dura mater, arachnoid and the pia mater. Brain region is subdivided as cerebrum, cerebellum, medulla oblongata, midbrain and pons. Readers are encouraged to refer to a text on anatomy[8], for a detailed anatomical description.

HEAD INJURY – LOAD CASES

Dynamic load causing injuries are divided into contact and non contact type[7]. Injuries due to contact type loads mainly occur due to impact on the head. They are further subdivided as injuries arising due to *direct contact loads* (which result in skull deformation and cause local brain deformation) and injuries arising due to *propagation of stress waves* from the impact region (causing negative pressure in the opposite side of the impact). Non contact type loads causes injuries due to inertial loads which arise due to linear and or angular acceleration / deceleration of the head.

HEAD INJURY ASSESSMENT FUNCTIONS

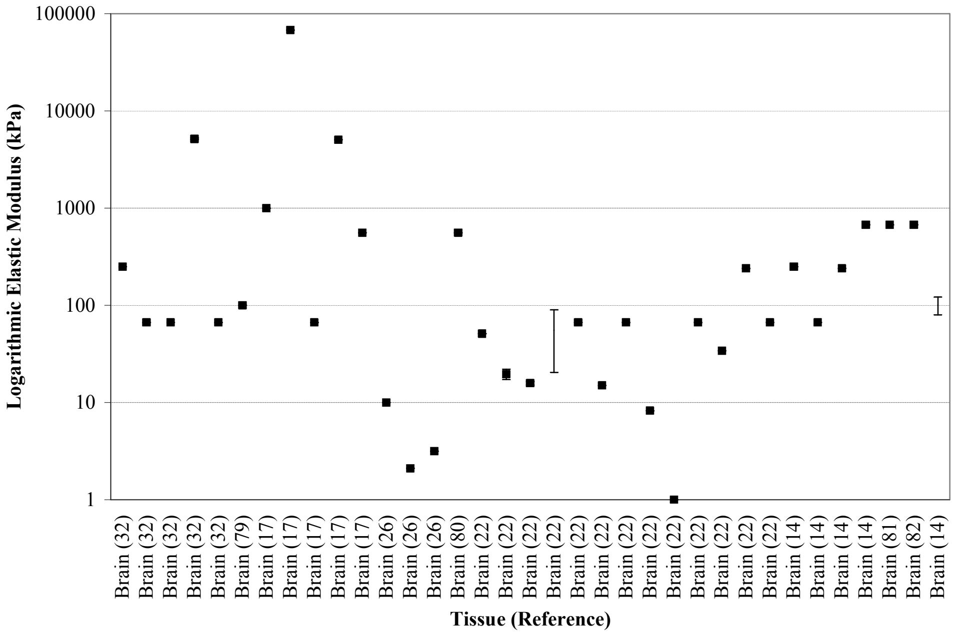
Several Injury criterions or injury assessment functions are developed to establish the degree of human tolerance to head impact. Head Injury Criterion (HIC) based on Wayne state tolerance curves (WSTC) is the most widely referred injury assessment function[9]. Other reported injury assessment functions include maximum linear acceleration, maximum linear acceleration with dwell times, Severity Index (SI), Angular acceleration combined with angular velocity change, Generalized Acceleration Model for Brain Injury Threshold (GAMBIT) – angular and linear acceleration[10]. These injury assessment functions predict injury risk from the external mechanical load and do not account for the internal mechanical response[11]. Hence the injuries risk at tissue level cannot be predicted in detail. Computational model with detailed geometry and biofiedilic material properties will overcome this difficulty and provide a better insight to injuries[6]. With substantial improvement in the geometry of the models using MRI and CT Scans, a review revealing the gaps in the tissue properties would help develop biofidelic finite element models. Hence a review of tissue properties extracted from experiments and those obtained by inverse mapping in finite element modeling is presented. We also discuss experiments conducted for developing the injury assessment functions.

EVOLUTION OF EXPERIMENTAL METHODS AND FINITE ELEMENT MODELS ON HEAD

Since the seventies, FE models have been used to study the behavior of head under impact loads. Khalil[12] predicted the impact loads causing brain damage by cavitation using three axisymmetric head models. Khalil[13] reviewed the issues in human head finite element models with respect to the experimental observations. Insufficient modeling accuracy, unrealistic boundary conditions related to neck attachments, scope for improvements in the brain tolerance criteria and required material properties were highlighted. Later, Sauren[14] reviewed the second generation finite element models published in the period 1982-1992. Large deformation models with nonlinear viscoelasticity were sought to overcome the limitations of linear elastic models. Visco-elastic models with incompressible theories were evolved for constituting the large strain and strain rate dependant behavior of brain tissue[15]. Zhou[16] developed a three-dimensional finite element model of human head and compared the responses of the homogenous and inhomogeneous human brain. The inhomogeneous brain model basically represents the gray and white matter with different material properties. This study conducted for frontal impacts reported variations in the shear responses due to the assumption of improper shear and volumetric properties showing the scope for experimental studies to measure shear strain in the brain due to impact. Claessens[17] collated the Young's Modulus data reported in literature and found its variation to be significant to influence the pressure and stresses in coup and counter coup regions. Kang[18] modeled the brain with linear, isotropic, viscoelastic material properties and validated the human head model against cadaver experiments. Newman[19] proposed a methodology to develop biomechanical criteria for mild traumatic brain injury using the data collected from soccer injuries. Updated Wayne state brain injury finite element model was used to reconstruct the incidents recorded during game. This study constituted the brain tissue as viscoelastic material under shear loading and elastic behavior under compressive loading. The deviatoric stress in shear loading was constituted as rate dependent and represented using shear relaxation modulus. Grey and white matter were subjected to different shear modulii. Followed by this study a new injury criterion, Head Impact Power (HIP) has been proposed to access the mild traumatic brain injury[10].

TISSUE LEVEL FINITE ELEMENT MODELS AND CONSTITUTIVE MODELS OF BRAIN TISSUE

A nonlinear viscoelastic constitutive model for brain tissue capable of predicting its response for 30% compression level was demonstrated by Miller[20] for very low strain (< $0.64s^{-1}$). A single-phase, linear viscoelastic model based on the strain energy function for loading velocities varying over five orders up to $0.64s^{-1}$ has been implemented in ABAQUS[21] for modeling the brain tissue. This linear model[21] requires fewer input material parameters than the earlier model[20]. Sarron[22] proposed a multi domain modeling technique to characterize the brain tissue and to identify the constitutive law parameters of each domain. Miller[23] tested the isolated brain soft tissues in uniaxial tension. The theoretical solution obtained from this study was valid only for isotropic, incompressible materials for moderate deformations (<30%) and cannot be used for load bearing tissues having directional properties. Miller[24] performed in vitro uniaxial tension experiments on swine brain tissue in finite deformation and developed a non-linear, viscoelastic model based on the generalization of the Ogden strain energy hyperelastic constitutive equation. This study has been extended for in vivo conditions and reports that the hyperelastic model predicts better response than the standard linear viscoelastic model[25]. Similarly, Kyriacou[26] compared the behavior of elastic, viscoelastic and poroelastic constitutive models and proposed compressible viscoelastic solid model suitable for low strain rate studies. Recently Miller[27] studied the behavior of brain tissue in unconfined condition with top and bottom surfaces of the tissue were glued with platens for compression loading. Arbogast[28] demonstrated the transversely isotropic behavior of brain stem under shear loading by analyzing the regional differences in the overall material stiffness and anisotropic mechanical properties of brain stem over a range of frequencies from 20-200 Hz, for 2.5-7.5 % engineering strain. Using this oscillatory shear loading experimental study, a fiber reinforced composite model composed of viscoelastic fibers surrounded by a viscoelastic matrix was developed to predict the response of anisotropic mechanical behavior[29]. Darvish[30] tested the quasilinear viscoelastic model with single hereditary integral and nonlinear viscoelastic model with multiple hereditary integrals to replicate the experimentally obtained nonlinear behavior of bovine brain tissue under shear loading. The experiments were reported for the forced vibrations from 0.5-200 Hz with finite amplitudes up to 20 % Lagrangian shear strain. The nonlinear model with multiple hereditary were found to be superior especially at frequencies above 44 Hz. Under finite strains in this study the linear complex modulus demonstrated nonrecoverable asymptotic strain behavior indicating the discrepancies with the assumed material properties of brain tissue. Brands[31] developed a three dimensional nonlinear viscoelastic model for predicting the brain tissue behavior under impact. The model predicts the strain dependent behavior up to 20 % strain and up to 8 s^{-1} strain rate. With devaitoric stress modeled as non-linear viscoelastic and volumetric stress as linear elastic, the brain tissue in this study was considered as nearly incompressible. Aida[32], proposed the influence of short term shear modulus and bulk modulus of brain tissue in shear response. The material properties of soft tissues in the head are categorized into tissue specific and indicated in the tables listed in appendix-A (Refer Table A1-Table A6). Figure 1 to Figure 4 show the properties graphically and indicate the mean or range values of the respective material properties.


100000
10000
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1
Logarithmic Elastic Modulus (kPa)
Brain (32)
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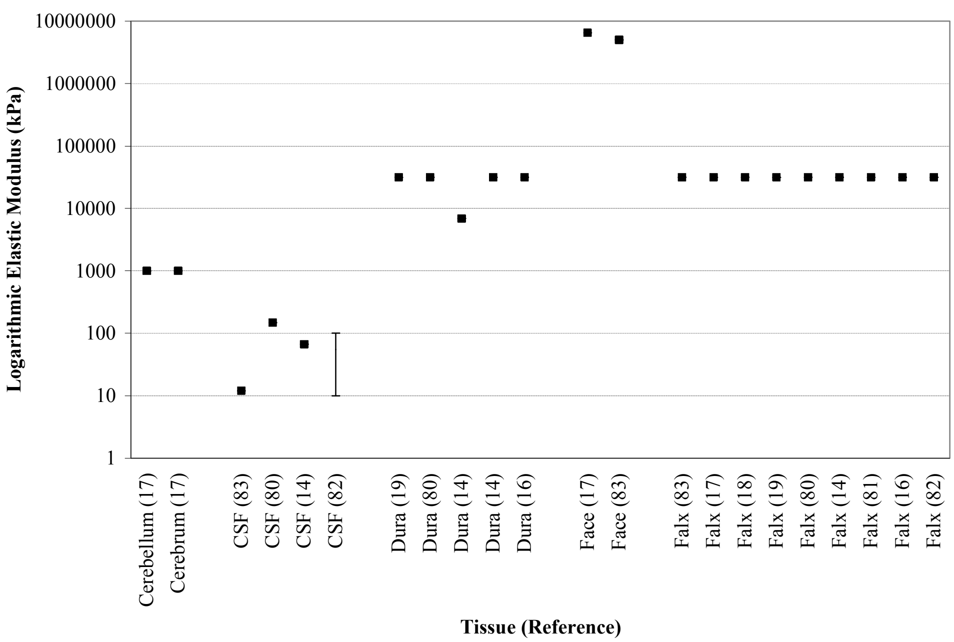
Tissue (Reference)

(a)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Logarithmic Elastic Modulus (kPa)
Cerebellum (17)
Cerebrum (17)
CSF (83)
CSF (80)
CSF (14)
CSF (82)
Dura (19)
Dura (80)
Dura (14)
Dura (14)
Dura (16)
Face (17)
Face (83)
Falx (83)
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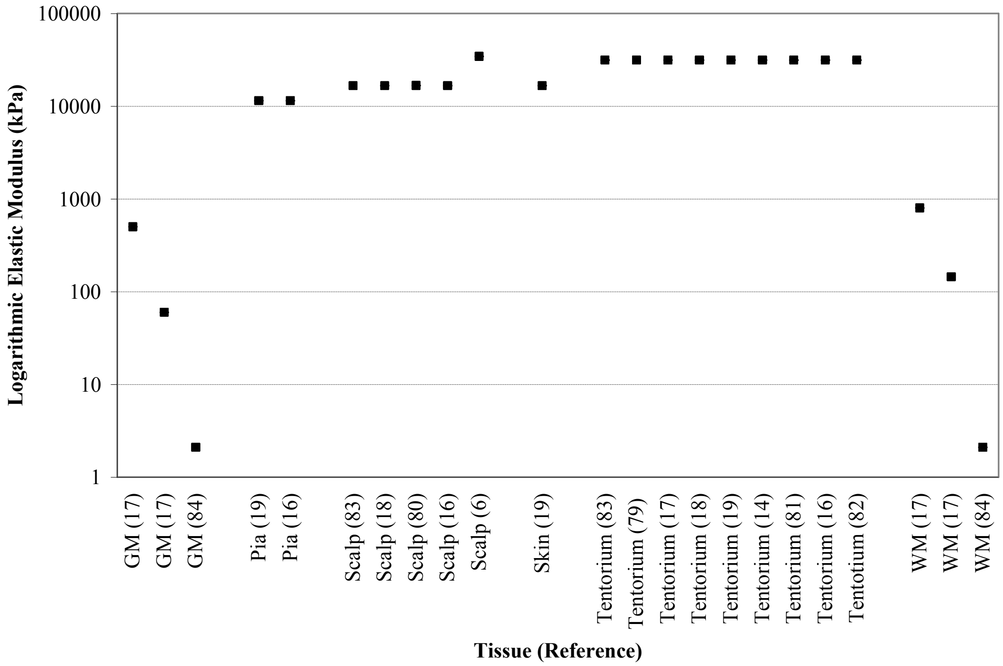
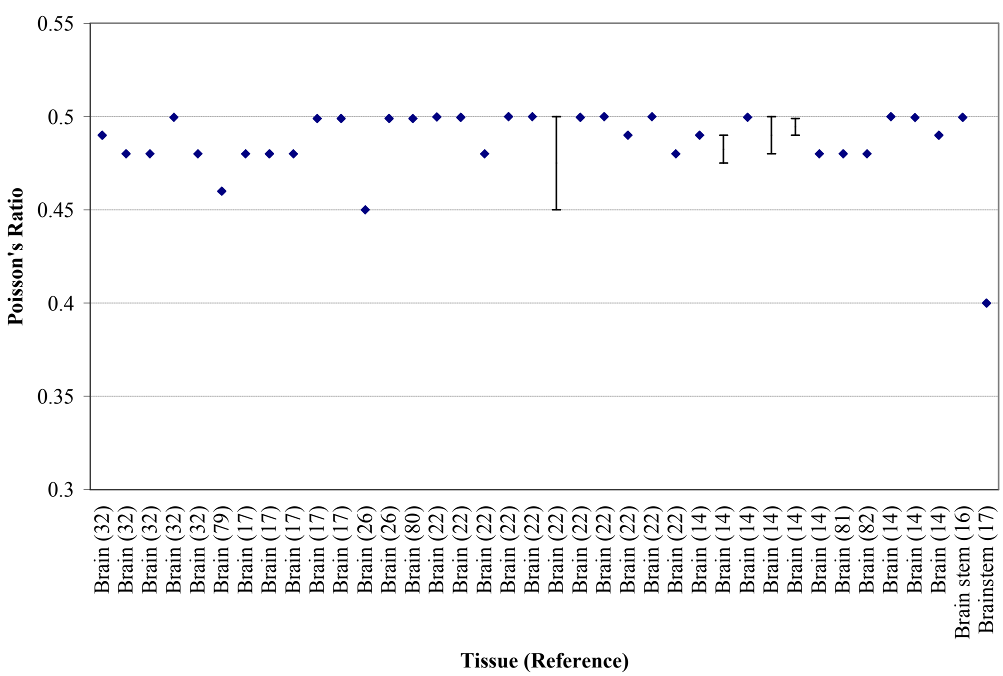
Tissue (Reference)

(b)



(c)

Figure 1 Elastic Modulus of different tissues a) Brain Tissue b) Head tissues (Cerebellum, CSF, Dura, Face tissue and Falx,) c) Head tissues continued (Gray Matter, Pia, Scalp Layer, Skin, Tentorium and White Matter)



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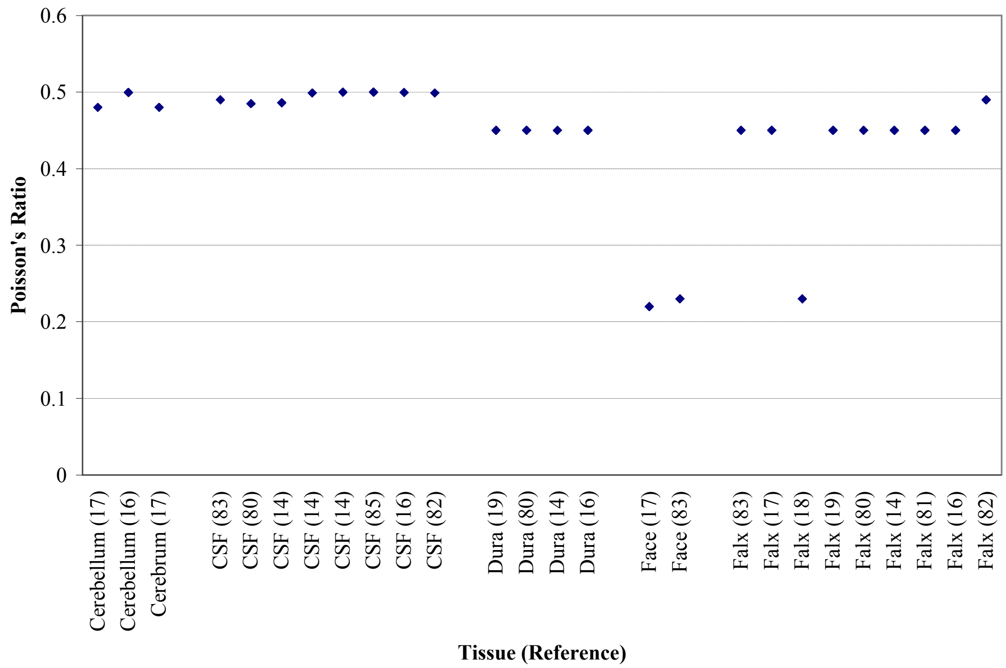

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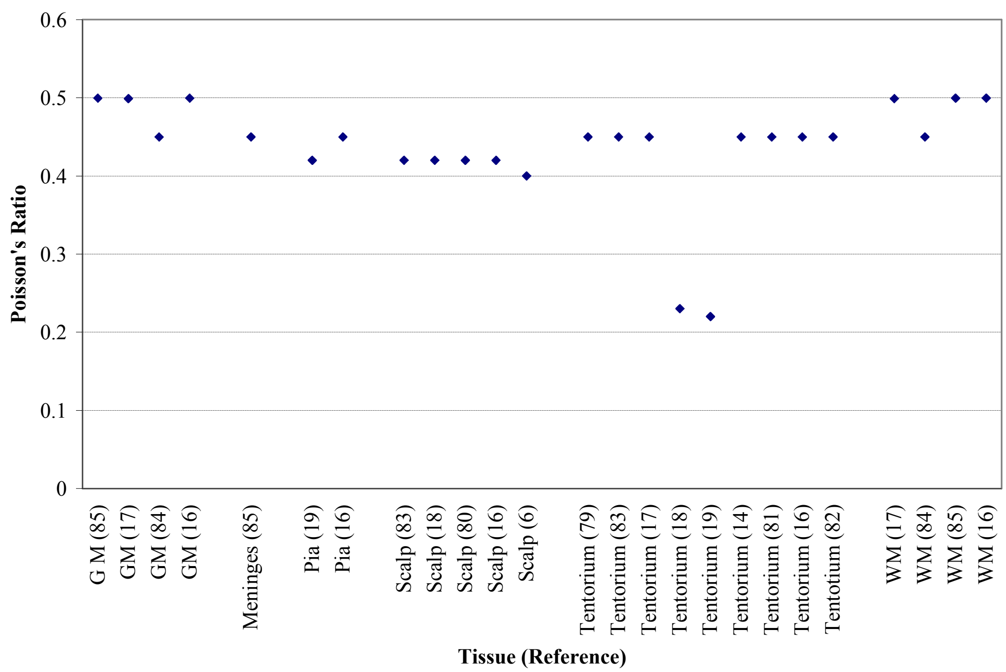

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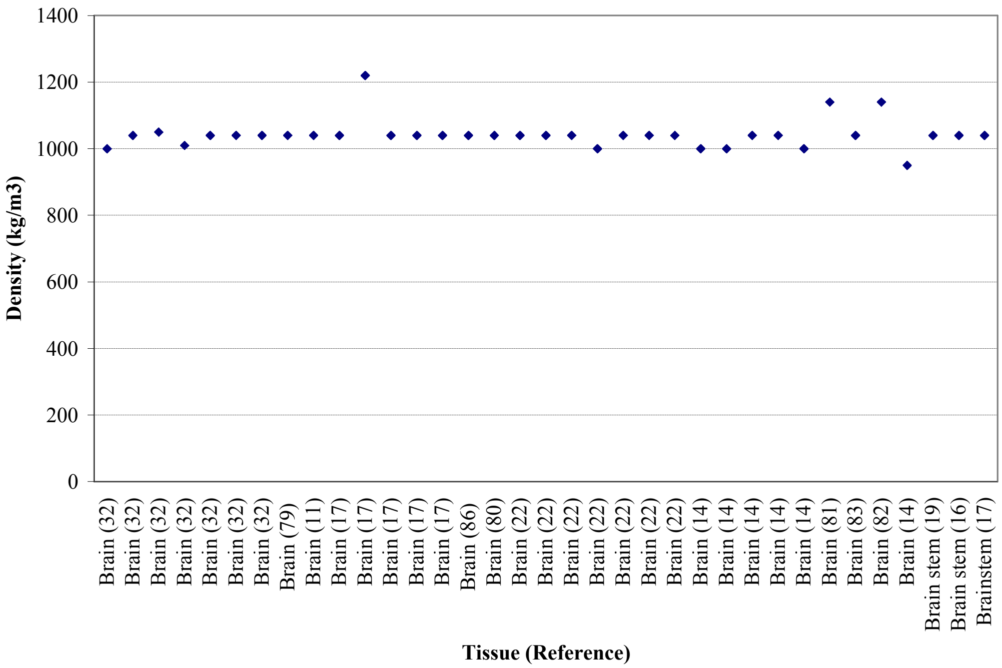
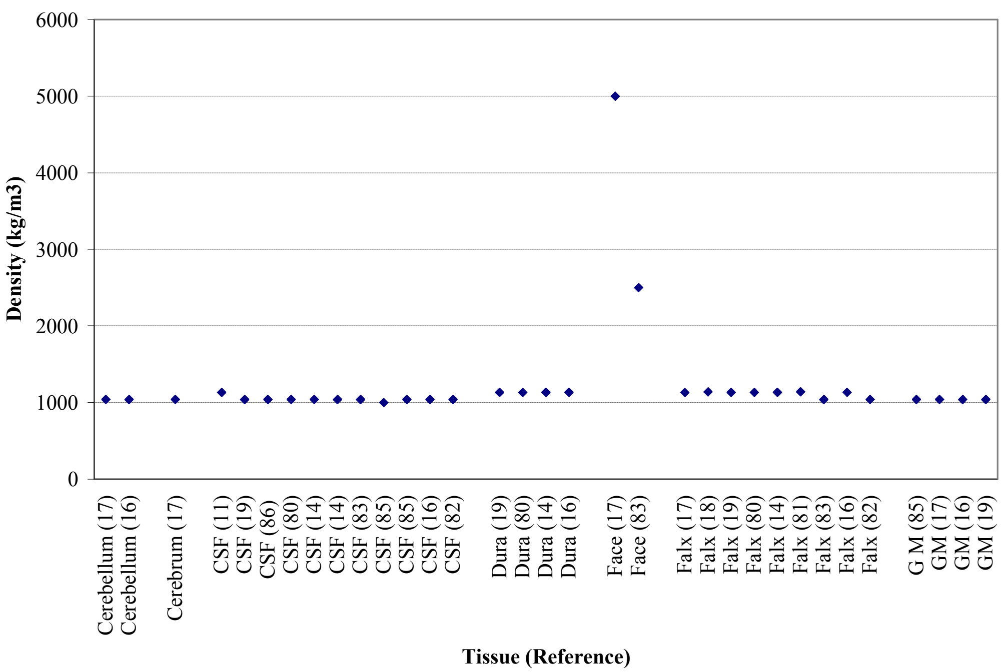
Figure 2 Poisson's Ratio of (a) brain tissues (b) Soft tissues in the head (Cerebellum, CSF, Dura, Face and Falx) (c) Soft tissues in the head (contd) (Gray Matter, Meninges, Pia, Scalp, Tentorium and White Matter)


Density (kg/m3)
Tissue (Reference)
0
200
400
600
800
1000
1200
1400
Brain (32)
Brain (79)
Brain (11)
Brain (17)
Brain (86)
Brain (80)
Brain (22)
Brain (14)
Brain (81)
Brain (83)
Brain (82)
Brain stem (19)
Brain stem (16)
Brainstem (17)

(a)


Density (kg/m3)
Tissue (Reference)
0
1000
2000
3000
4000
5000
6000
Cerebellum (17)
Cerebellum (16)
Cerebrum (17)
CSF (11)
CSF (19)
CSF (86)
CSF (80)
CSF (14)
CSF (14)
CSF (83)
CSF (85)
CSF (85)
CSF (16)
CSF (82)
Dura (19)
Dura (80)
Dura (14)
Dura (16)
Face (17)
Face (83)
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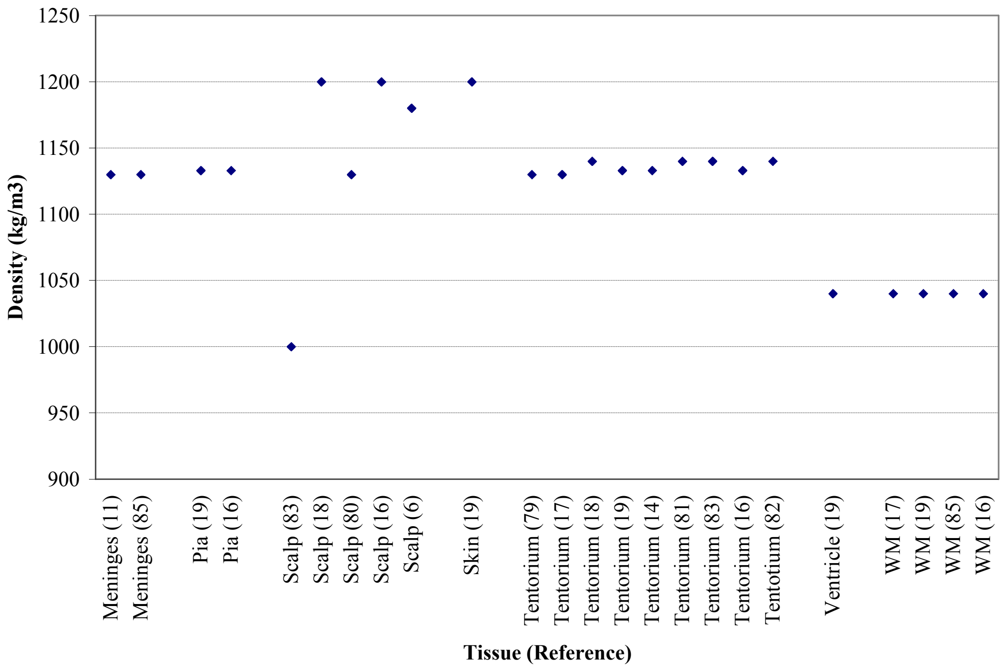
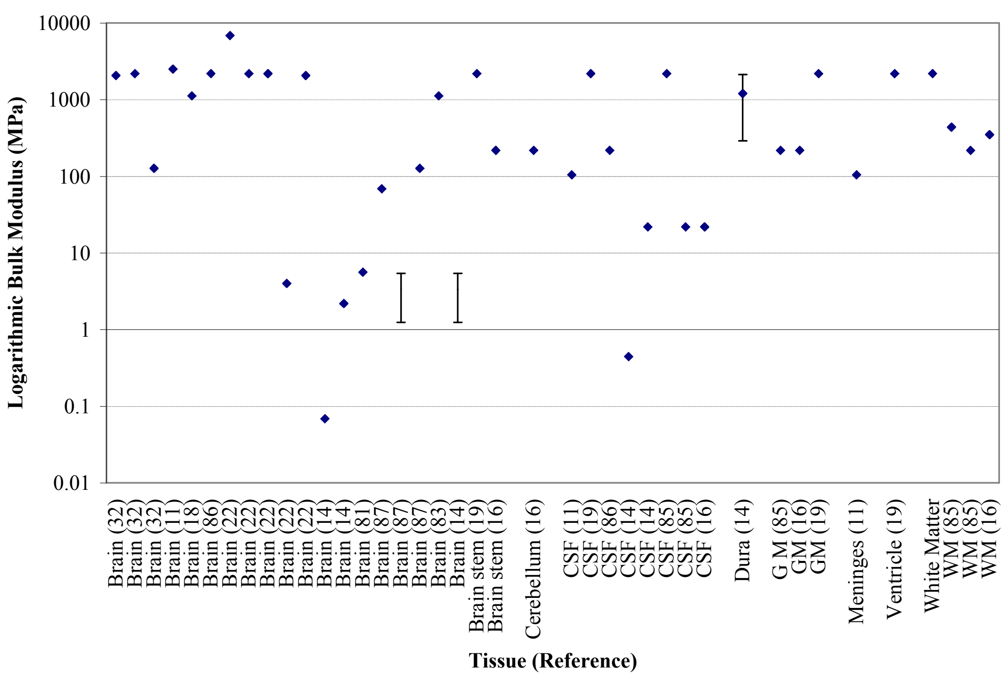
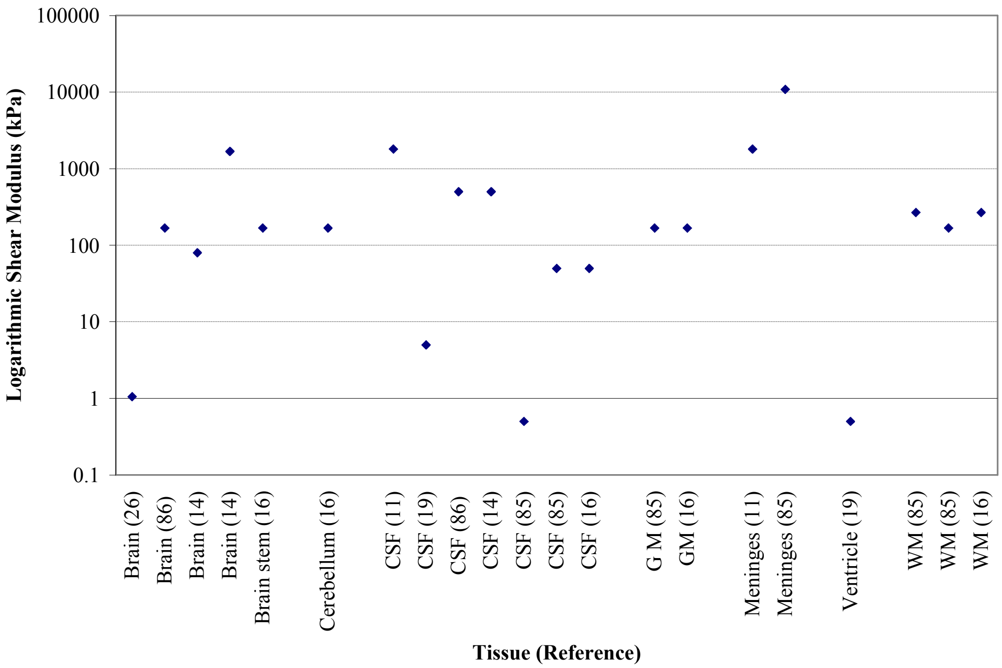


(c)

Figure 3 Density of (a) brain tissue (b) Brain soft tissues (Cerebellum, CSF, Dura, Face, Falx andGM) and (c) Brain soft tissues (contd) (Meninges, Pia, Scalp, Skin, Tentorium, Ventricle and White Matter)



(a)



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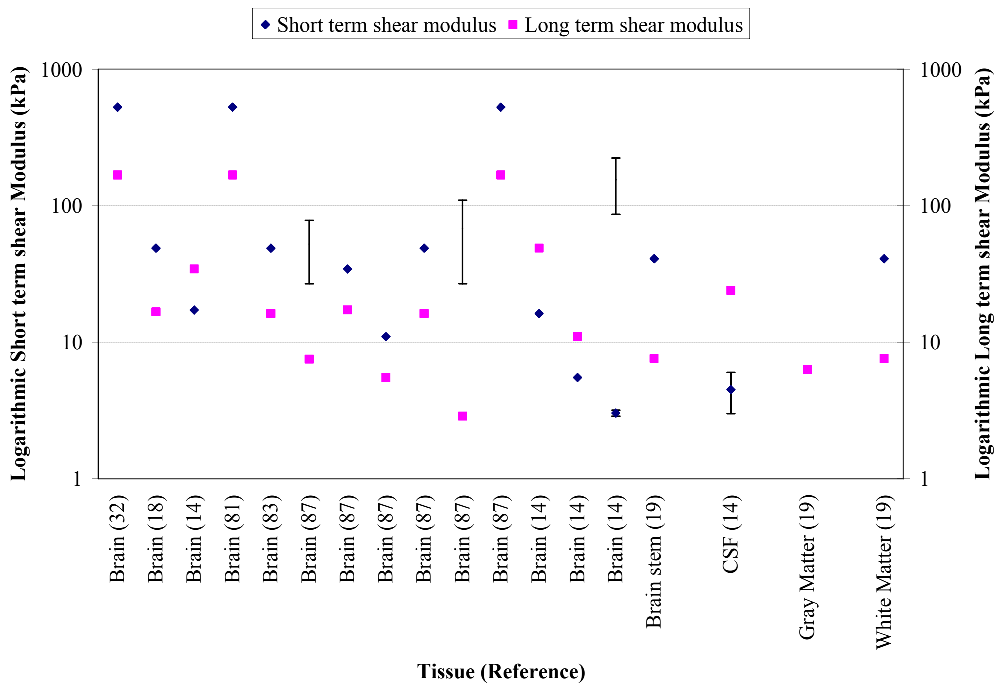

(c)

Figure 4 Bulk and Shear Modulus of Soft tissues (a) Bulk Modulus (b) Shear Modulus (c) Short and Long term Shear Modulus

Figure 1 shows that there is as much as a two order difference in the reported elastic modulus of brain tissue, grey matter and white matter whereas properties of tentorium and falx exhibit minor variations. Incompressible (nearly) modeling is found to be widely used to model the soft tissues in head as the Poisson's ratio indicated in **Figure 2** ranges from 0.4 to 0.5. Estimation of density is comparatively easier than the other properties and as shown in Figure 3, only minor variations are seen. Bulk modulus (Figure 4) varies in three orders of magnitude whereas only very few studies on shear modulus (Figure 4 (b)) are found. Dynamic shear moduli, short term and long term, properties (Figure 4 (c)) are available only for brain tissue but show a lot of variations.

NECK-SPINE

Neck injuries associated with excessive flexion-extension constitute the most prevalent trauma to occupants involved in motor vehicle accidents[33]. Severe neck injuries are extremely devastating because of possible damage to the cervical spinal cord as the cervical spine is responsible for the motion of the head as well as for protecting the spinal chord from injuries[34].

NECK-SPINE – ANATOMY OF SOFT TISSUES

Ligaments, intervertebral discs, cartilage, synovial membrane and muscles are the soft tissues in the neck-spine region. Ligaments stabilize the joints in the spine and restrict its motion. The cervical spinal ligaments are divided into lower cervical spinal ligaments and upper cervical spinal ligaments. The lower cervical spinal ligaments are anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), the capsular ligaments (CL) and ligamentum flavum (LF) whereas the upper cervical spine include apical ligament, the alar ligament and transverse ligament (TL). Articular cartilage reduces the friction in the zygapophysial joint during motion. The main function of intervertebral discs is to resist the compressive loading. Detailed anatomy of the neck muscles and its functions are well described by Mertz[34] and the soft tissues in cervical part have been reviewed by Yoganandan[35].

NECK-SPINE INJURY – LOAD CASES

Whiplash injuries are the most common injuries in occupants in automobile collisions. In addition the neck and the cervical spine are subjected to flexion (frontal collision), extension or hyperextension (rear end collision), lateral bending (Side impacts) and axial loads (tensile during airbag deployment and compressive during roof contact).

EVOLUTION OF EXPERIMENTAL METHODS AND NECK INJURY TOLERANCE

IN this section we briefly review volunteer as well as cadaver studies used to obtain neck injury tolerance values in various loading conditions. Mertz's investigation on whiplash injuries in late sixties and early seventies is a pioneer work in this area. A severity index (?? Name) for unsupported heads based on voluntary human tolerance limits has been proposed based on his investigations of the kinematics and kinetics of whiplash injuries[36]. Further, equivalent moment at the occipital condyle was proposed as the injury parameter for flexion and extension, and for hyperextension and hyperflexion[34]. These studies indicate that the neck muscles significantly influence the dynamic response of the spine by reducing the possibility of neck injury. Gadd[37] presented an injury criterion based on moment of the resistance offered by the neck in hyperextension and lateral flexion. Other criterion proposed for injury assessment are based on moment-angle response of the neck in low severity direct head impact loading[38], cervical damage as a function of applied force[39], dynamic tolerance for compressive loading[40], shear force and magnitude of eccentricity[41]. Passive responses of the cervical spine under torsion are time dependent[42]. Cervical motion segments in bending and axial torsion exhibit lower stiffness than lumbar motion segments[43]. Yoganandan[44] conducted rear sled impact tests to determine soft tissue related injuries on the head-neck complex. Injuries in soft tissues were reported on facet joints of the lower cervical spine. Svensson[45] presented an injury criterion using the pressure changes measured in the cervical spinal canal in swift extension-flexion using anaesthetized pigs. Later, Bostrom[46] developed a mathematical model to predict this pressure change as a function of volume change inside the spinal canal during neck bending in the saggital plane. Subsequently neck injury criterion (NIC), based on the relative acceleration and velocity between the top and the bottom of the cervical spine and the muscle influence on NIC were presented[46,47]. Although the NIC is widely followed among other injury assessment function for neck its inabilities towards representing the hyperextension injury mechanism and, flexion motion after rebound is to be noted[48]. Also NIC was primarily developed using nonhuman subjects for low velocity impacts, hence its validation for human injuries and for higher rates are still sought.

EVOLUTION OF FINITE ELEMENT MODELS

Though the above mentioned experimental studies were conducted with the soft tissues included, injuries can yet not be related to tissue behaviour. Over the years many finite element models have evolved. These FE models aim to help in injury assessment and overcome difficulties in cadaver testing such as the need of advanced experimental facilities, tissue availability, tissue measurements and time intensive preparation and repeatability.

Kleinberger[49] developed a 3D finite element model of human cervical spine for axial compression and frontal flexion to study the gross vertebral kinematics and deformation using reported experimental data[50]. This FE model included ALL, PLL, LF, CL and supraspinous ligament (SLL) as soft tissues but could not be validated for frontal flexion. This suggested that advanced material models, like viscoelastic and hyperelastic could be better than linear elastic model for modeling soft tissues. Lizee[51] developed a total human body model in which the disks are represented along with intervertebral joints. He has considered dynamic properties for thoracic and lumbar discs. Nitsche[52] developed a FE model of the human cervical spine and simulated volunteer tests[53,54] for frontal, lateral flexion and compression experiments[40,50,55]. Material properties of all components were assumed as homogenous and linear elastic and were taken from Yamada[56]. Vertebrae and the intervertebral discs are considered as isotropic whereas anisotropic material model was chosen for the articular cartilage and the ligaments. The fibers of the ligaments are in the direction of the applied tensile force. The articular cartilages between Cl and C2 are modeled with Young's modulus for compression. The maximum displacement in the simulation was lower than the test data because on use of linear elastic material properties. The variation in the material properties of the intervertebral discs and ligament structures representing the soft tissues alters the angular motion and the stresses in the inferior and the superior intervertebral discs of the cervical spine during flexion, extension, lateral bending and axial torsion[57]. Young's modulus of ligaments was found to have larger influence on the response whereas the Poisson's ratio of the spinal elements has little effect. Intervertebral discs transfer higher axial forces than shear forces through different regions of the disc under axial and eccentric loads in the ventral region and vice-versa in the dorsal region[58]. Facet joint anatomy idealized using a fluid model predict better response than hyperelastic solid model for compression, flexion, extension and lateral bending[59]. Other reported finite element models include a heck neck model[60] for rear impact velocities up to 2.6 m/s and a cervical spine model[61] to study the spine motion and analysis of C4-C6 unit[62].

MECHANICAL PROPERTIES OF SOFT TISSUE

A series of review on mechanical behavior of the cervical vertebrae and the soft-tissues of the cervical spine have been reported[63,64,65,66]. Structural properties measured in tensile failure load on isolated ligaments reveals that the ALL is the strongest and the PLL the weakest among the spinal ligaments studied[67]. Other ligaments included in this study were interspinous ligament (ISL), LF and joint capsule, which were tested for displacement rates ranging from 1 to 100 cm/s. Significant differences were reported between the animal and human ligaments in terms of structural properties as human ligaments are two to five times stronger than those of monkeys[67]. Posterior ligament tear under flexion and anterior longitudinal ligament tear under extension under dynamic loads[40]. The ligamentous upper cervical spine was significantly stronger in extension than in flexion where as upper cervical spine was stronger than the lower cervical spine in extension[68]. Segmental motions are statistically greater for females than for males at C2–C3, C4–C5, C5– C6, and C6–C7 levels, indicating that female soft tissues sustain greater magnitudes of stretch in rear impact[69]. Shear stiffness plays a major role in the stabilization of cadaver lumbar motion exhibits rate and directional dependency[70].

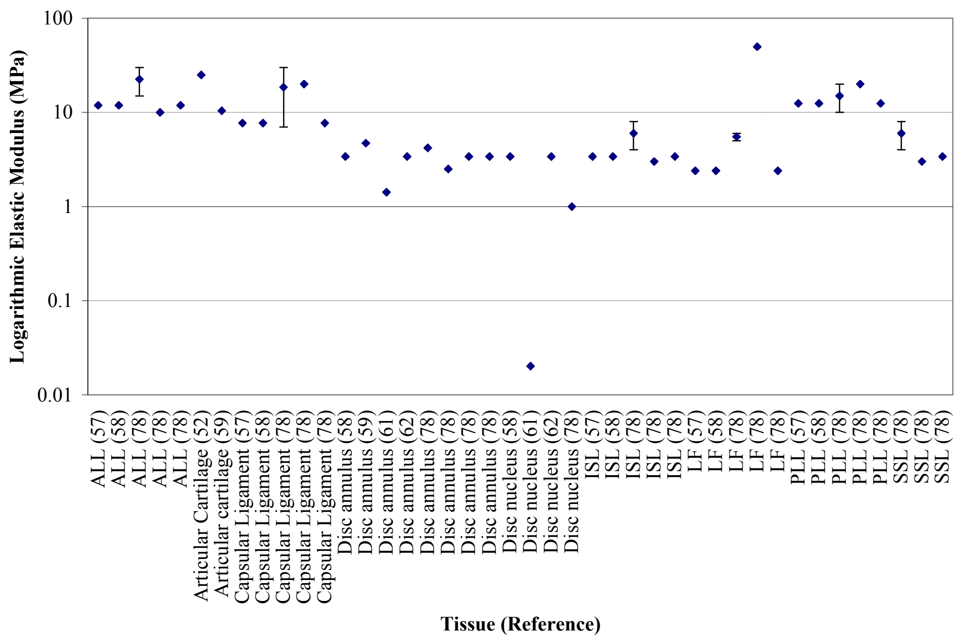

Figure 5 Elastic Modulus of the soft tissue in neck and spine region

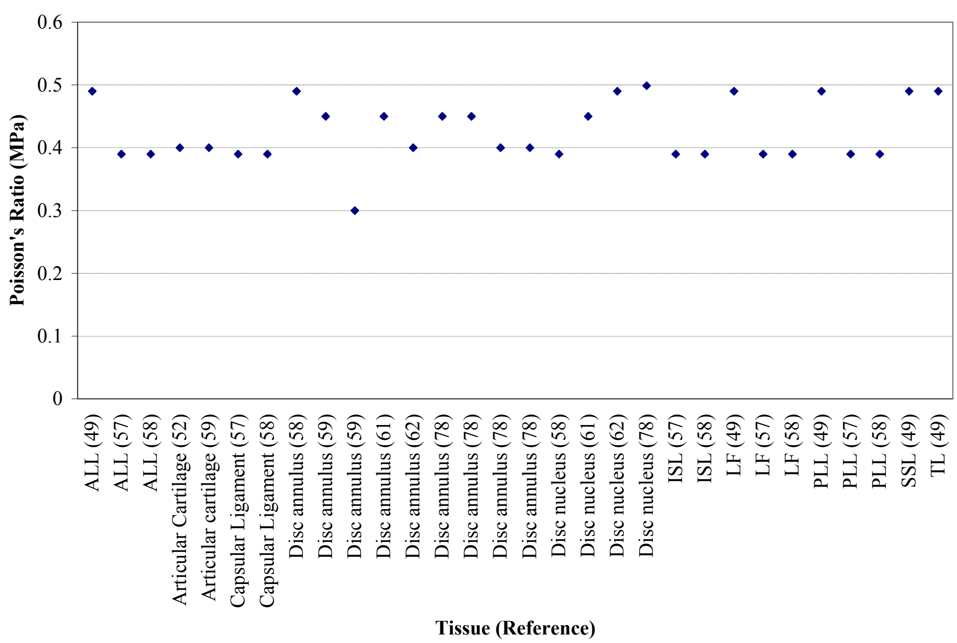

Figure 6 Poisson's Ratio of the soft tissue in neck and spine region

Failure loads of endplate and vertebral body of human lumbar vertebrae show rate dependency in compressive impact loads[71]. A kinematic analysis of head and neck unit conducted on cadavers indicates that the intervertebral disc is the most frequently injured tissue in frontal and lateral collisions, followed by LF in C1 to T4 region[72]. Several other studies have been performed on intervertebral disc to study its response to compressive[73,74] and dynamic loading[75]. Annulus fibrosus exhibits anisotropic shear properties through separate contributions from the matrix, the collagen fibers, and collagen fiber interactions[76]. Significant variations have been found in the shear modulus between the outer and inner annulus and influence of pre-strain in shear modulus. A linear material model with fiber-induced anisotropic behavior of annulus fibrosus has been proposed by Elliot[77] under tensile loading. Variation in the material properties of disc annulus has a significant influence on both the external biomechanical response and internal stress of the disc annulus and its neighboring hard bones[78].

The reported elastic modulus in the ALL and CL varies by a factor exceeding 2 while in the PLL, ISL and SLL the variation is less (Figure 5). Elastic modulus of disc annulus found to have little variation in most studies. Few data on Poisson's ratio of individual ligament tissues suggests the need for more tests (Figure 6). Dynamic properties are rarely reported in terms of short term and long term shear modulus for constituting the behavior in viscoelastic model.

Studies reported in the above section indicate the following observations in both head and neck-spine regions,

1. Most of the studies are performed at lower strain rates and methods to characterize the tissue at higher strain rates and related properties are needed.
2. Nonlinear viscoelasticity, anisotropy and rate dependency are not well characterized and more tissue level experiments are needed.
3. Muscles predominate the response in the neck spine region and are capable of altering the kinetics and kinematics of head. But studies including muscle behavior and its active tones are very few.
4. Advanced material models capable of predicting the above behavior have to be developed.

CONCLUSIONS

A body of knowledge about mechanical properties of soft tissues in head, neck and spine regions, assembled in recent years, is collated. Reported experimental methods, injury assessment functions and finite element models are investigated. Scatter and uncertainty among the reported material properties of soft tissues are observed on both static and dynamic properties. It is felt that isolated specimen tests aimed at developing the material models needed in finite element analysis should be prioritized. This will help understand the complex behavior of these tissues and subsequently aid in injury prediction using finite elements.

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APPENDIX –A- MECHANICAL PROPERTIES OF SOFT TISSUE RELATED TO HEAD

Table A1. Elastic Modulus of soft tissues

References (Other sources cited therein)	Soft tissue	Elastic modulus (MPa)
Brain		
32 (Chu 1994)	Brain	2.50E-01
32 (Hosey 1982)	Brain	6.67E-02
32 (Ruan 1991)	Brain	6.67E-02
32 (Ruan 1993)	Brain	5.06-5.26
32 (Ward 1980)	Brain	6.67E-02
79 (Claessens 1997)	Brain	1.00E-01
17 (Average)	Brain	1.00E+00
17 (Bandak 1995)	Brain	6.80E+01
17 (Kumaresan 1996)	Brain	6.67E-02
17 (Ruan 1991)	Brain	5.04E+00
17 (Ruan 1996)	Brain	5.58E-01
26 (Kaczmarek)	Brain	1.00E-02
26 (Miga 2000)	Brain	2.10E-03
26 (Miller 1997)	Brain	3.16E-03
80 (Ruan 1993)	Brain	5.58E-01
22 (Dimasi 1991)	Brain	5.10E-02
22 (Galford 1970)	Brain	1.72-2.20E-02
22 (Galford 1970)	Brain	1.51-1.65E-02
22 (Hirakawa 1981)	Brain	2.04-9E-02
22 (Hosey 1980	Brain	6.67E-02
22 (Koeneman 1966)	Brain	1.50E-02
22 (Kumaresan 1996)	Brain	6.67E-02
22 (Mendis 1995)	Brain	8.24E-03
22 (Miller 1997)	Brain	1.00E-03
22 (Ruan 1991)	Brain	6.67E-02
22 (Sahay 1992)	Brain	3.40E-02
22 (Ueno 1995)	Brain	2.40E-01
22 (Ward 1978)	Brain	6.67E-02
14 (Chu 1991)	Brain	2.50E-01
14 (Ruan 1991a)	Brain	6.67E-02
14 (Trosseille 1992)	Brain	2.40E-01
14 (Willinger 1992)	Brain	6.75E-01
81 (NA)	Brain	6.75E-01
82 (Ward 1975, Ruan 1992)	Brain	6.75E-01
14 (Lee 1990)	Brain (gel)	80-121.2E-03
17 (Average)	Brainstem	1.00E+00
Cerebellum		
17 (Average)	Cerebellum	1.00E+00
17 (Average)	Cerebrum	1.00E+00
CSF		
83 (Zhou 1996)	CSF	1.20E-02
80 (Ruan 1993)	CSF	1.49E-01
14 (Ruan 1991a)	CSF	6.67E-02
82 (Ward 1975, Ruan 1992)	CSF	10-100E-03

References (Other sources cited therein)	Soft tissue	Elastic modulus (MPa)
Dura		
19 (Shuk 1970)	Dura	3.15E+01
80 (Ruan 1993)	Dura	3.15E+01
14 (DiMasi 1991a, 1991b)	Dura	6.89E+00
14 (Ruan 1991a)	Dura	3.15E+01
16 (Ruan 1994)	Dura	3.15E+01
Face		
17 (Average)	Face	6.50E+03
83 (Zhou 1996)	Face	5.00E+03
Falx		
83 (Zhou 1996)	Falx	3.15E+01
17 (Ruan 1991)	Falx	3.15E+01
18 (Shuck 1972)	Falx	3.15E+01
19 (Shuk 1970)	Falx	3.15E+01
80 (Ruan 1993)	Falx	3.15E+01
14 (Ruan 1991a)	Falx	3.15E+01
81 (NA)	Falx	3.15E+01
16 (Ruan 1994)	Falx	3.15E+01
82 (Ward 1975, Ruan 1992)	Falx	3.15E+01
Gray Matter		
17 (Zhou 1995)	Gray Matter	5.00E-01
17 (Zhou 1996)	Gray Matter	1.88-10.1E-02
84 (Nagashima 1990, Baser 1992, Kalyanasundaram 1997)	Gray Matter	2.10E-03
Pia		
19 (Shuk 1970)	Pia	1.15E+01
16 (Ruan 1994)	Pia	1.15E+01
Scalp		
83 (Khalil 1977)	Scalp	1.67E+01
18 (Shuck 1972)	Scalp	1.67E+01
80 (Ruan 1993)	Scalp	1.67E+01
16 (Ruan 1994)	Scalp	1.67E+01
6	Scalp Layer	3.45E+01
Skin		
19 (Shuk 1970)	Skin	1.67E+01
Tentorium		
83 (Zhou 1996)	Tentorium	3.15E+01
79 (Ruan 1997)	Tentorium	3.15E+01
17 (Ruan 1991)	Tentorium	3.15E+01
18 (Shuck 1972)	Tentorium	3.15E+01
19 (Shuk 1970)	Tentorium	3.15E+01
14 (Ruan 1991a)	Tentorium	3.15E+01
81 (NA)	Tentorium	3.15E+01
16 (Ruan 1994)	Tentorium	3.15E+01
82 (Ward 1975, Ruan 1992)	Tentorium	3.15E+01

References (Other sources cited therein)	Soft tissue	Elastic modulus (MPa)
White Matter		
17 (Zhou 1995)	White Matter	8.00E-01
17 (Zhou 1996)	White Matter	2.27-12.2E-02
84 (Nagashima 1990, Baser 1992, Kalyanasundaram 1997)	White Matter	2.10E-03

Table A2. Poisson's ratio of soft tissues

References (Other sources cited therein)	Soft tissue	Poisson's ratio
Brain		
32 (Chu 1994)	Brain	0.49
32 (Hosey 1982)	Brain	0.48
32 (Ruan 1991)	Brain	0.48
32 (Ruan 1993)	Brain	0.4996
32 (Ward 1980)	Brain	0.48
79 (Claessens 1997)	Brain	0.46
17 (Average)	Brain	0.48
17 (Bandak 1995)	Brain	0.48
17 (Kumaresan 1996)	Brain	0.48
17 (Ruan 1991)	Brain	0.499
17 (Ruan 1996)	Brain	0.499
26 (Miga 2000)	Brain	0.45
26 (Miller 1997)	Brain	0.499
80 (Ruan 1993)	Brain	0.499
22 (Dimasi 1991)	Brain	0.4998
22 (Khalil 1982)	Brain	0.4996
22 (Kumaresan 1996)	Brain	0.48
22 (Mendis 1995)	Brain	0.5
22 (Miller 1997)	Brain	0.5
22 (Ruan 1991)	Brain	0.45-0.49999
22 (Ruan 1994)	Brain	0.4996
22 (Sahay 1992)	Brain	0.5
22 (Ueno 1995)	Brain	0.49
22 (Wang 1972)	Brain	0.5
22 (Ward 1978)	Brain	0.48
14 (Chu 1991)	Brain	0.49
14 (Lee 1987, Lighthall 1989, Ueno 1989, Ueno 1991)	Brain	0.475 &0.49
14 (Ruan 1991b)	Brain	0.4996
14 (Ruan 1991a)	Brain	0.48-0.49999492
14 (Trosseille 1992)	Brain	0.49-0.499
14 (Willinger 1992)	Brain	0.48
81 (NA)	Brain	0.48
82 (Ward 1975, Ruan 1992)	Brain	0.48
14 (Cheng 1990)	Brain (gel)	0.5
14 (Galbraith 1988, Tong 1989)	Brain (gel)	0.4995
14 (Lee 1990)	Brain (gel)	0.49
16 (Ruan 1994)	Brain stem	0.4996
17 (Average)	Brainstem	0.4
Cerebellum		
17 (Average)	Cerebellum	0.48
16 (Ruan 1994)	Cerebellum	0.4996
Cerebrum		
17 (Average)	Cerebrum	0.48
CSF		
83 (Zhou 1996)	CSF	0.49
80 (Ruan 1993)	CSF	0.485
14 (Ruan 1991b)	CSF	0.486
14 (Ruan 1991a)	CSF	0.499
14 (Trosseille 1992)	CSF	0.49999
85 (Ruan 1991)	CSF	0.49999
16 (Ruan 1994)	CSF	0.4996
82 (Ward 1975, Ruan 1992)	CSF	0.499
Dura		
19 (Shuk 1970)	Dura	0.45
80 (Ruan 1993)	Dura	0.45
14 (Ruan 1991a)	Dura	0.45
16 (Ruan 1994)	Dura	0.45
Face		
17 (Average)	Face	0.22
83 (Zhou 1996)	Face	0.23
Falx		
83 (Zhou 1996)	Falx	0.45
17 (Ruan 1991)	Falx	0.45
18 (Shuck 1972)	Falx	0.23
19 (Shuk 1970)	Falx	0.45
80 (Ruan 1993)	Falx	0.45
14 (Ruan 1991a)	Falx	0.45
81 (NA)	Falx	0.45
16 (Ruan 1994)	Falx	0.45
82 (Ward 1975, Ruan 1992)	Falx	0.49
Gray Matter		
85 (Ruan 1991)	Gray Matter	0.4996
17 (Zhou 1995)	Gray Matter	0.499
84 (Nagashima 1990, Baser 1992, Kalyanasundaram 1997)	Gray Matter	0.45
16 (Ruan 1994)	Gray Matter	0.4996
Meninges		
85 (Ruan 1991)	Meninges	0.45
Pia		
19 (Shuk 1970)	Pia	0.42
16 (Ruan 1994)	Pia	0.45

References (Other sources cited therein)	Soft tissue	Poisson's ratio
Scalp Layer		
83 (Khalil 1977)	Scalp	0.42
18 (Shuck 1972)	Scalp	0.42
80 (Ruan 1993)	Scalp	0.42
16 (Ruan 1994)	Scalp	0.42
6	Scalp layer	0.4
Tentorium		
79 (Ruan 1997)	Tentorium	0.45
83 (Zhou 1996)	Tentorium	0.45
17 (Ruan 1991)	Tentorium	0.45
18 (Shuck 1972)	Tentorium	0.23
19 (Shuk 1970)	Tentorium	0.22
14 (Ruan 1991a)	Tentorium	0.45
81 (NA)	Tentorium	0.45
16 (Ruan 1994)	Tentorium	0.45
82 (Ward 1975, Ruan 1992)	Tentorium	0.45
White Matter		
17 (Zhou 1995)	White Matter	0.499
84 (Nagashima 1990, Baser 1992, Kalyanasundaram 1997)	White Matter	0.45
85 (Ruan 1991)	White Matter	0.4996
16 (Ruan 1994)	White Matter	0.4996

Table A3. Density of soft tissues

References (Other sources cited therein)	Soft tissue	Density (kg/mm^3)
Brain		
32 (Chu 1994)	Brain	1000
32 (Hosey 1982)	Brain	1040
32 (Khalil 1974)	Brain	1050
32 (Khalil 1977)	Brain	1010
32 (Ruan 1991)	Brain	1040
32 (Ruan 1993)	Brain	1040
32 (Ward 1980)	Brain	1040
79 (Claessens 1997)	Brain	1040
11 (Ruan 1991)	Brain	1040
17 (Average)	Brain	1040
17 (Bandak 1995)	Brain	1220
17 (Kumaresan 1996)	Brain	1040
17 (Ruan 1991)	Brain	1040
17 (Ruan 1996)	Brain	1040
86 (Galford 1970, Sauren 1993)	Brain	1040
80 (Ruan 1993)	Brain	1040
22 (Hosey 1980	Brain	1040
22 (Khalil 1982)	Brain	1040
22 (Kumaresan 1996)	Brain	1040
22 (Mendis 1995)	Brain	1000
22 (Ruan 1991)	Brain	1040
22 (Ruan 1994)	Brain	1040
22 (Ward 1978)	Brain	1040
14 (Chu 1991)	Brain	1000
14 (Lee 1987, Lighthall 1989, Ueno 1989, Ueno 1991)	Brain	1000
14 (Ruan 1991b)	Brain	1040
14 (Ruan 1991a)	Brain	1040
14 (Trosseille 1992)	Brain	1000
81 (NA)	Brain	1140
83 (Zhou 1996)	Brain	1040
82 (Ward 1975, Ruan 1992)	Brain	1140
14 (NA)	Brain (gel)	950
19 (Shuk 1970)	Brain stem	1040
16 (Ruan 1994)	Brain stem	1040
17 (Average)	Brainstem	1040
Cerebellum		
17 (Average)	Cerebellum	1040
16 (Ruan 1994)	Cerebellum	1040
Cerebrum		
17 (Average)	Cerebrum	1040
CSF		
11 (Ruan 1991)	CSF	1130
19 (Shuk 1970)	CSF	1040
86 (Galford 1970, Sauren 1993)	CSF	1040
80 (Ruan 1993)	CSF	1040
14 (Ruan 1991b)	CSF	1040
14 (Ruan 1991a)	CSF	1040
83 (Zhou 1996)	CSF	1040
Zhou 1994	CSF	1000
85 (Ruan 1991)	CSF	1040
16 (Ruan 1994)	CSF	1040
82 (Ward 1975, Ruan 1992)	CSF	1040
Dura		
19 (Shuk 1970)	Dura	1133
80 (Ruan 1993)	Dura	1130
14 (Ruan 1991a)	Dura	1133
16 (Ruan 1994)	Dura	1133
Face		
17 (Average)	Face	5000
83 (Zhou 1996)	Face	2500
Falx		
17 (Ruan 1991)	Falx	1130
18 (Shuck 1972)	Falx	1140
19 (Shuk 1970)	Falx	1133
80 (Ruan 1993)	Falx	1130
14 (Ruan 1991a)	Falx	1133
81 (NA)	Falx	1140

References (Other sources cited therein)	Soft tissue	Density (kg/mm^3)
83 (Zhou 1996)	Falx	1040
16 (Ruan 1994)	Falx	1133
82 (Ward 1975, Ruan 1992)	Falx	1040
Gray Matter		
85 (Ruan 1991)	Gray Matter	1040
17 (Zhou 1995)	Gray Matter	1040
16 (Ruan 1994)	Gray Matter	1040
19 (Shuk 1970)	Gray Matter	1040
Meninges		
11 (Ruan 1991)	Meninges	1130
85 (Ruan 1991)	Meninges	1130
Pia		
19 (Shuk 1970)	Pia	1133
16 (Ruan 1994)	Pia	1133
Scalp		
83 (Khalil 1977)	Scalp	1000
18 (Shuck 1972)	Scalp	1200
80 (Ruan 1993)	Scalp	1130
16 (Ruan 1994)	Scalp	1200
6	Scalp layer	1180
Skin		
19 (Shuk 1970)	Skin	1200
Tentorium		
79 (Ruan 1997)	Tentorium	1130
17 (Ruan 1991)	Tentorium	1130
18 (Shuck 1972)	Tentorium	1140
19 (Shuk 1970)	Tentorium	1133
14 (Ruan 1991a)	Tentorium	1133
81 (NA)	Tentorium	1140
83 (Zhou 1996)	Tentorium	1140
16 (Ruan 1994)	Tentorium	1133
82 (Ward 1975, Ruan 1992)	Tentorium	1140
Ventricle		
19 (Shuk 1970)	Ventricle	1040
White Matter		
17 (Zhou 1995)	White Matter	1040
19 (Shuk 1970)	White Matter	1040
85 (Ruan 1991)	White Matter	1040
16 (Ruan 1994)	White Matter	1040

Table A4. Shear Modulus of soft tissues

References (Other sources cited therein)	Soft tissue	Shear Modulus (MPa)
26 (Miller)	Brain	1.05E-03
86 (Galford 1970, Sauren 1993)	Brain	1.68E-01
14 (Ruan 1991b)	Brain	1.68E+00
14 (Lee 1987, Lighthall 1989, Ueno 1989, Ueno 1991)	Brain	8.00E-02
16 (Ruan 1994)	Brain stem	1.68E-01
16 (Ruan 1994)	Cerebellum	1.68E-01
11 (Ruan 1991)	CSF	1.81E+00
19 (Shuk 1970)	CSF	5.00E-03
86 (Galford 1970, Sauren 1993)	CSF	5.00E-01
14 (Ruan 1991b)	CSF	5.00E-01
85	CSF	5.00E-04
85 (Ruan 1991)	CSF	5.00E-02
16 (Ruan 1994)	CSF	5.00E-02
85 (Ruan 1991)	Gray Matter	1.68E-01
16 (Ruan 1994)	Gray Matter	1.68E-01
11 (Ruan 1991)	Meninges	1.81E+00
85 (Ruan 1991)	Meninges	1.09E+01
19 (Shuk 1970)	Ventricle	5.00E-04
85	White Matter	2.68E-01
85 (Ruan 1991)	White Matter	1.68E-01
16 (Ruan 1994)	White Matter	2.68E-01

Table A5. Bulk Modulus of soft tissues

Reported Author (Taken from other references)	Soft tissue	Bulk modulus (MPa)
Brain		
32 (Khalil 1974)	Brain	2.07E+03
32 (Khalil 1977)	Brain	2.19E+03
32 (Ruan 1993)	Brain	1.28E+02
11 (Ruan 1991)	Brain	2.50E+03
18 (Shuck 1972)	Brain	1.13E+03
86 (Galford 1970, Sauren 1993)	Brain	2.19E+03
22 (Dimasi 1991)	Brain	6.89E+03
22 (Khalil 1982)	Brain	2.19E+03
22 (Ruan 1994)	Brain	2.19E+03
22 (Ueno 1995)	Brain	4.00E+00
22 (Wang 1972)	Brain	2.07E+03
14 (DiMasi 1991a, 1991b)	Brain	6.89E-02
14 (Ruan 1991b)	Brain	2.19E+00
81 (Willinger 1995)	Brain	5.63E+00
87 (DiMasi 1991)	Brain	6.89E+01
87 (Lee 1990)	Brain	1.25-5.44
87 (Ruan 1994)	Brain	1.28E+02
83 (Zhou 1996)	Brain	1.13E+03
14 (NA)	Brain (gel)	1.25-5.44
19 (Shuk 1970)	Brain stem	2.19E+03
16 (Ruan 1994)	Brain stem	2.19E+02
16 (Ruan 1994)	Cerebellum	2.19E+02

Reported Author (Taken from other references)	Soft tissue	Bulk modulus (MPa)
CSF		
11 (Ruan 1991)	CSF	1.05E+02
19 (Shuk 1970)	CSF	2.19E+03
86 (Galford 1970, Sauren 1993)	CSF	2.19E+02
14 (NA)	CSF	4.45E-01
14 (Ruan 1991b)	CSF	2.19E+01
85	CSF	2.19E+03
85 (Ruan 1991)	CSF	2.19E+01
16 (Ruan 1994)	CSF	2.19E+01
Dura		
14 (Ruan 1991a)	Dura	0.219-2.19E+03

Reported Author (Taken from other references)	Soft tissue	Bulk modulus (MPa)
Gray Matter		
85 (Ruan 1991)	Gray Matter	2.19E+02
16 (Ruan 1994)	Gray Matter	2.19E+02
19 (Shuk 1970)	Gray Matter	2.19E+03
Meninges		
11 (Ruan 1991)	Meninges	1.05E+02
Ventricle		
19 (Shuk 1970)	Ventricle	2.19E+03
White Matter		
19 (Shuk 1970)	White Matter	2.19E+03
Zhou 1994	White Matter	4.39E+02
85 (Ruan 1991)	White Matter	2.19E+02
16 (Ruan 1994)	White Matter	3.49E+02

Table A6. Shear Modulus of soft tissues (Dynamic Properties)

Reported Author (Taken from other references)	Soft tissue	Short term shear modulus (MPa)	Long Term shear modulus (MPa)	Decay Constant (1/s)
32 (Ruan 1993	Brain	5.28E-01	1.68E-01	35
18 (Shuck 1972)	Brain	4.90E-02	1.67E-02	145
14 (DiMasi 1991a, 1991b)	Brain	1.72E-02	3.45E-02	100
81 (Galford 1970)	Brain	5.28E-01	1.68E-01	35
83 (Zhou 1996)	Brain	4.90E-02	1.62E-02	145
87 (Cheng 1990)	Brain	35-70E-03	7.51E-03	50-300
87 (DiMasi 1991)	Brain	3.45E-02	1.72E-02	100
87 (Galbraith 1988)	Brain	1.10E-02	5.51E-03	200
87 (Khalil 1977)	Brain	4.90E-02	1.62E-02	145
87 (Lee 1990)	Brain	26.9-110E-03	2.87E-03	50
87 (Ruan 1994)	Brain	5.28E-01	1.68E-01	35
14 (Cheng 1990)	Brain (gel)	1.62E-02	4.90E-02	145
14 (Galbraith 1988, Tong 1989)	Brain (gel)	5.51E-03	1.10E-02	200
14 (NA)	Brain (gel)	2.87E-03-18E-03	26.9-110E-03	50
19 (Shuk 1970)	Brain stem	4.10E-02	7.60E-03	700
14 (NA)	CSF	3-6E-03	2.40E-02	50
19 (Shuk 1970)	Gray Matter	3.40E-02	6.30E-03	700
19 (Shuk 1970)	White Matter	4.10E-02	7.60E-03	700

APPENDIX –B- MECHANICAL PROPERTIES OF SOFT TISSUE RELATED TO NECK AND SPINE

Table B1 Elastic Modulus of soft tissues

Reported Author (Taken from other references)	Soft tissue	Elastic modulus (MPa)
57(Kempson 1979, Pintar 1986, Yamada 1970)	ALL	11.9
58 (Average)	ALL	11.9
78 (Goel 1998)	ALL	15-30
78 (Maurel 1997)	ALL	10
78 (Yoganandan 1998)	ALL	11.9
52 (Yamada 1970)	Articular Cartilage (Neck)	25
57 (Kempson 1979, Pintar 1986, Yamada 1970)	Capsular Ligament	7.7
58 (Average)	Capsular Ligament	7.7
78 (Goel 1998)	Capsular Ligament	7-30
78 (Maurel 1997)	Capsular Ligament	20
78 (Yoganandan 1998)	Capsular Ligament	7.7
58 (Average)	Disc annulus	3.4
59 (Average)	Disc annulus	4.7
59 (Average)	Disc annulus	500
61 (Wu 1993)	Disc annulus	1.42
62 (Kleinberger 1993)	Disc annulus	3.4
78 (Goel 1998)	Disc annulus	4.2
78 (Maurel 1997)	Disc annulus	2.5
78 (Ng 2001)	Disc annulus	3.4
78 (Yoganandan 1998)	Disc annulus	3.4
58 (Average)	Disc nucleus	3.4
61 (Wu 1993)	Disc nucleus	0.02012
62 (Kleinberger 1993)	Disc nucleus	3.4
78 (Ng 2001)	Disc nucleus	1
59 (Average)	Facet Articular cartilage	10.4
57 (Kempson 1979, Pintar 1986, Yamada 1970)	Interspinous Ligament	3.4
58 (Average)	Interspinous Ligament	3.4
78 (Goel 1998)	Interspinous Ligament	4-8
78 (Maurel 1997)	Interspinous Ligament	3
78 (Yoganandan 1998)	Interspinous Ligament	3.4
57 (Kempson 1979, Pintar 1986, Yamada 1970)	LF	2.4
58 (Average)	LF	2.4
78 (Goel 1998)	LF	5-10
78 (Maurel 1997)	LF	50
78 (Yoganandan 1998)	LF	2.4
57 (Kempson 1979, Pintar 1986, Yamada 1970)	PLL	12.5
58 (Average)	PLL	12.5
78 (Goel 1998)	PLL	10-20
78 (Maurel 1997)	PLL	20
78 (Yoganandan 1998)	PLL	12.5
78 (Goel 1998)	Supraspinous ligament	4-8
78 (Maurel 1997)	Supraspinous ligament	3
78 (Yoganandan 1998)	Supraspinous ligament	3.4

Table B 2 Poisson's Ratio of soft tissues

Reported Author (Taken from other references)	Soft tissue	Poisson's Ratio
49	ALL	0.49
57 (Kempson 1979, Pintar 1986, Yamada 1970)	ALL	0.39
58 (Average)	ALL	0.39
52 (Yamada 1970)	Articular Cartilage	0.4
57 (Kempson 1979, Pintar 1986, Yamada 1970)	Capsular Ligament	0.39
58 (Average)	Capsular Ligament	0.39
58 (Average)	Disc annulus	0.49
59 (Average)	Disc annulus	0.45
59 (Average)	Disc annulus	0.3

Reported Author (Taken from other references)	**Soft tissue**	**Poisson's Ratio**
61 (Wu 1993)	Disc annulus	0.45
62 (Kleinberger 1993)	Disc annulus	0.4
78 (Goel 1998)	Disc annulus	0.45
78 (Maurel 1997)	Disc annulus	0.45
78 (Ng 2001)	Disc annulus	0.4
78 (Yoganandan 1998)	Disc annulus	0.4
58 (Average)	Disc nucleus	0.39
61 (Wu 1993)	Disc nucleus	0.45
62 (Kleinberger 1993)	Disc nucleus	0.49
78 (Ng 2001)	Disc nucleus	0.499
58 (Average)	End plate	0.4
59 (Average)	End plate	0.3
61 (Wu 1993)	End plate	0.25
62 (Saito 1991)	End plate	0.4
59 (Average)	Facet Articular cartilage	0.4
61 (Wu 1993)	Facet joint	0.25
57 (Kempson 1979, Pintar 1986, Yamada 1970)	Interspinous Ligament	0.39
58 (Average)	Interspinous Ligament	0.39
49	LF	0.49
57 (Kempson 1979, Pintar 1986, Yamada 1970)	LF	0.39
58 (Average)	LF	0.39
49	PLL	0.49
57 (Kempson 1979, Pintar 1986, Yamada 1970)	PLL	0.39
58 (Average)	PLL	0.39
49	Supraspinous ligament	0.49
49	TL	0.49

April 22, 2006

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Dear Sir,

Kindly find enclosed four copies of a manuscript of our paper, titled, "Review of Mechanical Properties of Human Body Soft Tissues in the head neck and spine", co-authored by Dr. S Mukherjee, myself and B Karthikeyan, along with a CD containing the soft version for consideration for publication in the Institution of Engineers, Journal of Mechanical Engineering. I request you to kindly consider for the same. The author form and the paper submission forms are also enclosed. Being a review paper the word count (not including figures, tables and appendices) has reached 3657 and we have had to include 6 figures instead of your limit of 5. I hope you will be able to consider the same as in a review paper of this kind, it was very difficult to stick to these limits and we believe that this paper will have a very strong archival value and in the interest of quality of Indian Journals, it should appear in Indian Journals.

Yours truly,

(A Chawla)