SOFT TISSUE INJURIES AND INJURY TOLERANCE LEVELS

A.M. Nahum, M.D.

University of California at San Diego

Dennis C. Schneider

General Motors Research Laboratories
Warren, Michigan

The superficial soft tissues are the most common anatomic injury site. For various reasons, this fact has been ignored in most statistical tabulations of injury frequency by anatomic location.

The superficial soft tissues play important roles in total body function and may be classified in the following way:

(1) protection
(2) identification
(3) physiologic function

The soft tissues provide the coverings and contours which are the very essence of human identification. In addition, they perform diverse physiologic functions which include temperature regulation, sensation, and responses to various chemical stimuli. They protect the body from substances which would be harmful to deeper structures such as bacteria. They also protect the body against many mechanical forces by resisting penetration. They also serve to absorb energy and distribute loads which may be applied externally. One special group of soft tissues, the muscles, plays an additional role. The muscles provide resistance when forces are applied to bones to which they are attached. Important examples of this protective aspect during impact are the resistance at the cervical spine to bending produced by muscle contraction. Compression of the thoracic cage is also effectively changed by contraction of the chest musculature. This is of particular importance if internal thoracic trauma can be related to the degree of chestwall deflection.

For the purposes of this overview, soft tissues have been divided into two categories:

(1) superficial soft tissues
    a. skin
    b. subcutaneous tissues
    c. muscle
(2) organs and organ systems.

The thickness and composition of the superficial soft tissues varies widely over the body surfaces for any particular age group. These variations may be accounted for by the thickness of the skin, the amount of subcutaneous tissue and fat, and the development and quality of the regional musculature. Thus the skin over the face is relatively thin, contains varying thicknesses of soft tissue and a relatively thin layer of muscle. Over the anterior abdominal wall the skin is thicker, the subcutaneous tissues and fat are generally much thicker, and there is a relatively well developed muscular layer.

The important organs and organ systems to be discussed are contained in three body cavities:

(1) cranial
(2) thoracic
(3) abdominal

The brain within the cranium is shielded almost entirely by the soft tissue layers of the scalp overlying the cranial bones. The only major opening at the base, the foramen magnum, permits a connection between brain and spinal cord.

The contents of the thoracic cavity, the lungs and cardiovascular system, are fully shielded by the ribs and overlying soft tissues anteriorly and posteriorly. Superiorly the narrowed thoracic inlet, cervical spine, clavicle and first rib provide protection. Inferiorly a thin fibro-muscular sheet, the diaphragm, separates the thoracic and abdominal cavities. The abdominal cavity is shielded superiorly by the lower ribs and inferiorly by the pelvic brims. However, the anterior and lateral boundaries are somewhat exposed.

Statistical studies of injury frequency by location may be difficult to evaluate. In survivors, it may be difficult to detect all of the injuries sustained in closed cavities without extensive surgical exploration. Studies of accident fatalities often suffer from the lack of a precise post-mortem examination. Even when these examinations are performed it is difficult to evaluate the relative severity of multiple injuries and assign them a relative role as factors in the causation of death.

THE ABDOMEN

Tonge, et al (1972) tabulated the injury sites of 908 traffic crash victims and noted that the liver was most commonly injured, occurring in 25.5% of the total fatalities with a distribution of 32% of car drivers, 28.4% of car passengers, 24.4% of motorcyclists, 20% of pedestrians and 10.8% of pedal cyclists. The spleen was second in order of injury frequency with involvement in 20.3% of all victims and a distribution of 20.7% of car drivers, 25.9% of passengers, 12.1% of motorcyclists, 18.9% of pedestrians and 8.1% of pedal cyclists. Injuries to other intra-abdominal structures in descending order of frequency were kidneys, small bowel, colon, urinary bladder, internal reproductive organs, pancreas, adrenals, stomach, and duodenum. Major vessel injuries occurred in 3.1%. In a general statistical review of blunt abdominal trauma in an unselected population, Griswold and Collier (1961) indicated the following frequencies of injury: spleen, 26.2%, kidneys, 24.2%, intestines, 16.2%, liver, 15.6%, abdominal wall, 3.6%, mesentery, 2.5%, pancreas, 1.4%.

Clearly, the solid organs are at greatest risk with the spleen, kidneys, and liver at the top of the list. The intestines, particularly the small intestine, closely follow. The preponderance of drivers in the at-risk population and their special vulnerability to the frontal and left-sided impacts provide special impact risks to the spleen, liver and kidneys. These organs have a thin capsule and are soft and friable as well.

There are few known English language reports of biomechanical studies of isolated abdominal organs. Hardy (1972) studied fifty cases of liver injury after fatal blunt trauma. The usual type of injury observed was a shattering or splitting of the liver with extensive hematoma formation. In 26 cases only one lobe was involved, usually the right, while in 24 cases both lobes were involved. Mays (1966) demonstrated superficial tears of the liver at a level of 30 foot pounds and wide destruction at 360 foot pounds.

THE THORAX

Tonge (1972) reviewed the distribution of thoracic injuries for a series of fatal accidents. Contusions or lacerations of one or both lungs occurred in 33.5% of all casualties with a distribution of 36.3% of drivers, 37.5% of passengers, 31.7% of motorcyclists, 29.7% of pedal cyclists and 28.5% of pedestrians. Injuries to the heart occurred in 11.6% of the total, with a frequency of 19.5% in drivers, 11.1% of passengers, 9.8% of motor cyclists, 7.3% of pedestrians and 5.4% of pedal cyclists. Injuries to the aorta occurred in 8.8% of the total and were most common in pedestrians, (10.4%).

Again, isolated studies of thoracic organs in impact situations are rare. Studies of animals have purposely been excluded as being of limited value when discussing human injury responses to impact.

CRANIUM

Tonge, et al (1972) tabulated injury distributions for the head in a group of accident fatalities and noted that 81.2% sustained superficial soft tissue injuries to scalp, face and ears. Injuries to the brain occurred in 48.3% of the total with a distribution of 73% of pedal cyclists, 63.4% of motor cyclists, 51.3% of passengers, 48.7% of pedestrians, and 39.4% of drivers. Brain contusions were more common than lacerations. Slatis (1962) noted in a series of 230 fatalities that cerebral contusions were the most common brain injury and occurred mainly in the temporal and frontal lobes.

TRAUMA PATTERNS ASSOCIATED WITH RESTRAINT SYSTEMS

With the advent of restraint systems, usually consisting of seat and/or upper torso belts, new types of soft tissue injuries have appeared. The most common injuries can be divided into soft tissue and osseous. The soft tissue injuries usually consist of abrasion and/or contusion of the anterior and lateral abdominal walls. However, several intra-abdominal soft tissue structures are injured most commonly. The intestines and/or their mesenteric attachments appear to be highest on the list. This has included ruptures, tears or perforations of the jejunum, colon, ileum. The mechanism of injury has been postulated as direct compression of a loop of bowel with relatively incompressible contents, or shearing and disruption of the ligaments and mesenteric attachments of the intestines, particularly the small intestine.

The pregnant uterus may also be at greater risk during impact with an overlying seat belt. The bladder, especially when distended, may also be ruptured by the sudden compressive loading. The liver, spleen, and kidneys do not appear to be at risk due to seat belt exposure as they are during usual impact conditions with unrestrained occupants.

BIOMECHANICS OF SOFT TISSUES

Despite the variety of soft tissues present in the human; skin, heart muscle, tendon, brain tissue, etc., in general they all can be classified as non-homogeneous, anisotropic materials. Additionally, the soft tissues are highly non-linear in their elastic response. As a consequence of these attributes, a quantitative description of their material properties, time dependent stress-strain characteristics, and mechanisms of failure is a considerable undertaking. Understandably, the analytical development of a general theory for the biomechanical behavior of biological soft tissues is a multi-phase task. General material considerations of homogeniety, isotropy, the presence of elastic elements, viscous effects and time dependency are just a portion of the questions raised. A one-dimensional description of tissue mechanics must logically precede biaxial and three dimensional theoretical treatments. In order to obtain a fundamental understanding of how the various constituents of tissue interact to effect a composite response, most scientific investigation up to this time has concerned itself with environments that minimized the external forces acting on the tissue. It is for this reason that the bulk of research presently available has dealt with the behavior of soft tissue at physiologic levels of stress and strain rates. Minimal information exists describing tissue reponse at traumatic levels of stress and/or strain rates commonly encountered in vehicular accident situations. Tolerance information in general is empirically based due to the lack of a theoretical framework to describe the various tissue and organ systems.

The existing literature on this subject is sparce and in some cases misleading in its interpretation. While extensive work has been done in the field of system response and tolerance, as evidenced in other sections of these proceedings, little has been accomplished in defining material properties and mechanical response of isolated organs and tissues. A reasonable degree of sophistication is required in experimental design and laboratory apparatus employed. Control over tissue state (temperature, moisture content, etc.) is necessary in excised specimen testing. Because of tissue's viscoelastic behavior, investigation over a broad spectrum of strain rates is appropriate to ascertain inertial effects at high rates of loading. In vivo testing of tissue material properties requires that the sample be sufficiently isolated from adjacent viscera to exclude undesired constraints.

For purposes of clarity, this discussion will be limited to investigation of skin and brain tissue. Emphasis will be placed on skin due to its relative coverage in the literature. Moreover, in many respects it shares common analytical approaches and experimental techniques with other soft tissue types.

No attempt will be made to document all the relevant work in the literature as several excellent sources are available: Crisp (1970), Snyder (1970) and Fung (1970). Rather, the major analytical approaches and experimental techniques will be discussed and pertinent works from these areas highlighted.

SKIN

Although great effort has been expended in the realm of skin rheology, a governing stress-strain relationship for soft tissue has not been established. Fung (1967) has proposed a theoretical outline for the description of the non-linear response of soft tissue in simple elongation. The outline was based on experimental results obtained from tensile tests of excised rabbit mesentery. It was found that the hysteresis curve showed little change when the strain rate was increased, an order of magnitude (0.0508 to 0.508 cm/min) leading Fung to conclude that the irreversible portion of the stress-strain law of biological material is not linear viscoelastic. The mathematical formulation worked well when applied to published data on the series element of the heart, striated muscles and the skin at low levels of stress. To accommodate the non-linearities and strain-history characteristics of soft tissue he concludes, in part, that the convention of assigning a constant Young's modulus of elasticity to a tissue is erroneous.

Due to the large strains encountered in biological tissues new techniques of analyses departing from classical elasticity theory are required. Veronda and Westmann (1970) utilized the principles of finite elasticity to develop uniaxial stress-strain relationships for large deformations in cat skin. The analyses used admittedly ignored the rate sensitive and anisotropic properties of the tissue, but correlated well with experimental tensile tests of the excised cat tissue. Jamison, et al, (1968) discussed an experimental technique for obtaining discrete viscoelastic models of guinea pig skin. The quick freeze technique devised by Marangoni et al (1966) (described later in this review) was used to prepare the excised tissue for testing. Creep testing performed on the tissue and the response found to be dependent on stress magnitude and time effects. Specimen samples whose in vivo orientation was orthogonal demonstrated anisotropic behavior. Moreover, a previous strain history dependence was found in load recycling experiments. Their findings concluded that guinea pig skin is an anisotropic non-linear viscoelastic material with a memory of its previous strain history.

Dynamic response of bovine muscle tissue in compression was examined by McElhaney and Byers (1967). All specimens were taken from the femoral shaft area of a single animal. Samples were tested up to 3 days after excision. In the interim they were refrigerator stored. Constant volume compression was assumed in computing the instantaneous strain area of tissue. At strain rates approaching 1,000 sec^{-1} the shape of the stress-strain curve did not exhbit all of the non-linearities present at moderate rates of strain (1 - 100 sec^{-1}). They hypothesized that this was a result of the viscoelastic properties of the muscle collagen approaching those of the intracellular muscle fluid.

The structural response of human skin to uniaxial tension is described by Ridge and Wright (1966). Specimens comprised of human biopsy and autopsy material taken from the forearm and abdominal regions were exposed to rates of extension from 0.0125 to 3.20 inches /min. The extension process was divided into three phases; (1) the straightening out and orientation of the specimen collagen fibers, (2) the extension of oriented fibers, and (3) yielding, as individual collagen fibers broke down. The same authors (1965) found evidence that the stiffness of collagen fibers tended to decrease in humans beyond age 40, although the collagen contact of skin remained constant with increasing age.

Unfortunately, information regarding the quantification of physical parameters required to produce trauma in overlying tissue is minimal. Attention has been focussed on the breaking strength of experimental wounds, (Geever, etal,(1966), Glaser et al (1965)

Beckwith et al (1963) Gadd, et al (1967) discussed the ability of skin and associated underlying tissues to resist breakage under slowly and rapidly applied loading. A penetrometer device was devised to provide a means of pressing a hardened steel indenter of known dimensions through a tissue sample and obtain a reading of the force required for perforation. It was hypothesized that skin fails more often in a tensile or cohesive manner than from a shearing or cutting action. In a later study, Nahum et al (1973) utilized unembalmed human cadaver tissue samples and exposed them to impact loading between rigid parallel surfaces (1.0 in^2 contact area) at strain rates up to 630 sec^{-1}. Data obtained included force-time history, coefficient of restitution and the load versus deflection hysteresis loop. A typical parietal scalp specimen withstood a peak force of 610 lbs. at 0.150 inches of compression during an applied pulse of risetime of 1.0 milliseconds. The resulting visible crush was of the order of 0.5 to 1 mm. A technique to qualitatively indicate the conditions necessary to produce lacerative facial trauma was also described. Experiments were carried out over a period of days and tissue was refrigerated during the period between tests.

Due to the empirical nature of much of the research involving soft tissues it is advisable to exercise great care in experimental design. Marangoni et al (1966) demonstrated radical differences in maximum stress, strain, and stiffness of guinea pig skin as affected by the storage technique after tissue excision from the animal. Sections of the excised tissue were stored in constant temperature chambers at 1.6°C and 37°C. Both chambers were at 100 per cent relative humidity. The third group of tissue was rapidly frozen with liquid nitrogen (- 224°C) and stored in a carbon dioxide cold storage chamber at -92.8°C. At predetermined time intervals tissue was removed from storage, immersed in a 24°C saline bath and subjected to uniaxial tensile tests at a strain rate of 1.0 in/min. The maximum stress and stiffness of the 1.6°C and 37.8°C specimens showed an initial increase (150 and 260 per cent, respectively, for the 37.8°C samples) within the first hour of storage while the opposite was true of the maximum strain and work input characteristics (30 and 33 per cent decrease, respectively, for the 37.8°C samples). It was concluded that low temperature (liquid nitrogen) storage had the least effect on the mechanical properties examined.

BRAIN TISSUE

Before an effective rationale describing the mechanism of traumatic head injury can be established, a description of the material properties of the relevant tissues should be at hand (Goldsmith, (1966). Ommaya (1968) in an extensive search of the literature, discovered only three sources of information on the mechanical properties of brain tissue, (Franke, 1954), (Dodgson, 1962), (Koeneman, 1966). Since that time additional investigations have been completed and initial results are now available.

Fallenstein, et al (1969) measured the dynamic complex shear modulus of in vitro samples of human brain. Specimens from eight human brains were subjected to sinesoidal shear stress input (9-10 Hz) provided by an electro-mechanical test device. Experimental parameters examined included, effects of time after death, refrigeration of material and shear strain dependence. Preliminary results of in vivo experiments on Rhesus monkey brain were also offered. The dynamic shear modulus was determined to fall between

$6 - 11 \times 10^3$ dyn/cm^2 for human post-mortem tissue. This value is just below that obtained by von Gierke, et al (1952) for in vivo human muscular tissue. The calculated dynamic shear viscosity of 56-96 P bears the same relationship to von Gierke's data. The in vitro testing of human brain which indicated high internal damping correlated with in vivo testing of monkey brain at zero blood pressure. In vitro storage was at a temperature of 3°C since preliminary testing indicated that gross changes occurred in the brain modulus upon freezing.

A viscoelastic study of scalp, brain and dura was undertaken by Galford and McElhaney (1970). Human and Rhesus monkey brain were exposed in vitro to creep and relaxation experiments. Although instantaneous strains were of the order of 20 - 40 per cent during the creep tests the departure from linear viscoelastic theory was small, supporting their conclusion that brain can be considered a linear viscoelastic material. It was not determined whether the difference in creep response between monkey and human brain was due to different elapsed time of testing following death. No significant difference was observed in relaxation properties of human and monkey brain tissue.

An in situ comparison of live, dead, and fixed brain tissue in Rhesus monkeys was studied by Metz et al (1970). The experimental technique utilized the fluid inflation of a small elastic cylinder within the brain tissue. The fluid pressure with the cylinder was measured and thick walled elastic cylinder analysis was applied to the brain tissue allowing computation of the tissue elastic modulus. It was found that the modulus increased with strain, varying between 0.1 and 6 dyn/cm^2 for live and dead tissue and 3 and 14 dyn/cm^2 for formalin fixed tissue. It was concluded that little change in elasticity occurs after death while the greatest change is apparent in the formalin fixed tissue. No mention was made of the time lapse between formalin perfusion and fixed tissue testing. The change in tissue state as a function of time following embalming is well known, thereby casting doubt on the uniqueness of the modulus values obtained for formalin fixed material. Data gathered for live and dead tissue agreed well with results obtained by Koeneman (1966) and Galford and McElhaney (1970). Post mortem density values of brain dura and scalp material for human and Rhesus monkey donors were reported by Barber, et al (1970). A total of 55 human subjects and 20 monkeys were evaluated. Average density for human brain was given to be 1.081 gm/cm^3 and 1.100 for monkey brain tissue.

A necessary adjunt to defining the bulk material properties of brain is a description of tissue failure modes as they relate to deformation fields within the brain. The numerous in vivo system investigations previously reported, and those now in progress, concerning the patho-physiological changes of the skull and cranial contents when exposed to an abrupt change in acceleration field will be fully understood only when the mechanism of localized tissue failure is revealed. Much clinical information is available describing the gross tissue pathology resulting from impulsive loading of the skull. Lacking, however, is a resolution of the physical mechanisms by which brain tissue is rendered incompetent. Toward this end, two studies being presented at these proceedings are of relevance. Chalupnik, et al (1973) has examined the breakdown of the blood-brain barrier as evidenced by the rupture of small blood vessels. Experiments were performed in vivo on Rhesus monkeys employing a rigid indenter to predictably deform the brain tissue. Histologic slides of the deformed tissue were then evaluated for the presence of free red blood cells.

The red cell count was correlated with the imposed deformation gradient.

The disruption of the parasagittal bridging veins was examined by Lowenhielm, (1973). Data was presented relating the elongation and elongation rate of bridging veins. Experiments were performed at various strain rates and the maximum elongation at rupture was shown to be highly time dependent.

CONCLUSIONS

Soft tissue injuries are the most common anatomic category of accidental trauma. This area has received little statistical or experimental work due in part to ignorance of the epidemiologic factors and in part to lack of interest in injury protection. While superficial soft tissue injuries are rarely life threatening, they often constitute grave cosmetic defects with permanent psychic effects. Injuries to organs and organ systems within the three main body cavities are often life threatening. These organs may share many similar properties with these superficial tissues and lend themselves to similar modes of analysis. With full knowledge of the widespread occurrence of soft tissue injuries, increased studies of their properties is mandatory.

Evident from a review of the literature is the lack of information usable by those engaged in vehicular accident research. Work accomplished to date, with few exceptions, has not treated the response of soft tissue to loading conditions typically seen in automotive crash environments.

Since the viscoelastic characteristics of soft tissue dominate its response, further high strain rate experimentation is required. Departing from the physiologically oriented tensile tests, further studies on the compressive loading aspects of overlying soft tissue would provide needed information on the force attenuating and energy absorbing characteristics of skin and subcutaneous tissue. Also, how these parameters vary with respect to regional differences in body tissue (e.g. abdomen vs. scalp) is not understood.

Post-mortem tissue deterioration and its attendant effects on mechanical properties has received little attention. Mechanical properties and the physical basis of failure mechanisms of isolated organs (lung, liver, spleen, etc.) are virtually unknown.

Much further investigation is needed before a biomechanical understanding of how the human body responds to an impact environment is reached.

REFERENCES

1. Barber, T.W., Brockway, J.A. and Higgins, L.S.
   The density of tissues in and about the head.
   Acta neurol.scand. 46: 85-92, (1970

2. Beckwith, T.G., Glaser, A.A., Prevenslik, Brody, G.S., and White, W.L.
   Standardization of methods for measuring the mechanical properties of wounds.
   ASME, - paper no. 63 - WA - 276 (1963)

3. Chalupnik, J.D., Alvord, E.C. and Kobayashi, A.S.
   Progress in the determination of fragility of brain tissue.
   International Conference on the Biokinetics of Impacts; Amsterdam (1973)

4. Crisp, J.D.
   Properties of tendon and skin. In Y.C. Fung, (eds.)
   Biomechanics. Its Foundations and Objectives. Prentice-Hall, Inc.
   Englewood Cliffs, New Jersey. pp. 141-79 (1970)

5. Dodgson, M.C.H.
   Colloidal structure of brain.
   Biorheology, I: pp. 21-30 (1962)

6. Follenstein, G.T., Hulce, V.D., and Melvin, J.W.
   Dynamic mechanical properties of human brain tissue.
   J.Biomechanics. 2: pp 217-226 (1969)

7. Franke, E.K.
   The response of the human skull to mechanical vibrations.
   Wright-Patterson Air Force Base, Ohio, WADC Tech.Rept. 54-24 (1954)

8. Fung, Y.C.
   Elasticity of soft tissues in simple elongation.
   Am.J.Physiol. 213 (6): 1532-1544 (1967)

9. Fung, Y.C.
   Stress-strain-history relations of soft tissues in simple elongation.
   In Y.C. Fung: (eds) Biomechanics Its Foundations and Objectives.
   Prentice-Hall, Inc., Englewood Cliffs, N.J. pp. 181-208 (1970)

10. Gadd, C.W., Peterson, F.J., and Lange, W.A.
    Strength of skin and its measurement with special application to trauma.
    In Biomechanics Monograph. ASME, New York, pp. 184-91 (1967)

11. Galford, J.E. and McElhaney, J.H.
    A viscoelastic study of scalp, brain and dura.
    J.Biomechanics (3), pp. 211-221 (1970)

12. Geever, E.F., Levenson, S.M. and Manner, G.
The role of noncollagenous substances in the breaking strength of experimental wounds.
Surgery 60 (2): 343-51 (1966)

13. Glaser, A.A., Marangoni, R.D., Must, J.S., Beckwith, T.G., Brody, G.S. Walker, G.R. and White, W.L.
Refinements in the methods for the measurement of the mechanical properties of unwounded and wounded skin.
Med.Electron.Biol.Eng. 3: 411 - 19 (1965)

14. Goldsmith, W.
The physical processes producing head injuries.
In W.F. Caveness and A.E. Walker, (eds)
Head injury, Lippincott, Philadelphia, pp. 350-382 (1966)

15. Griswold, R.A. and Collier, H.S.
Blunt Abdominal Trauma.
SGO, 112, 309, (1961)

16. Hardy, K.J.
Patterns of Liver Injury after Fatal Blunt Trauma.
SGO, 134, 1 (1972)

17. Jamison, C.E., Marangoni, R.D. and Glaser, A.A.
Viscoelastic properties of soft tissue by discrete model characterization.
J.Biomechanics (1): 33-46 (1968)

18. Koeneman, J.B.
Viscoelastic properties of brain tissue.
Unpublished M.S. Thesis, Case Institute of Technolocy

19. Lowenhielm, P.
On the mechanism of cortical bridging vein rupture.
International Conference on the Biokinetics of Impacts: Amersterdam (1973)

20. Marangoni, R.D., Glaser, A.A. Must, J.S., Brody, G.S., Beckwith, T.G., Walker, G.R. and White, W.L.
Ann.N.Y. Acad.Sci., (136): 439-454 (1966)

21. McElhaney, J.H., and Byers, E.F.
Dynamic response of biological materials.
ASME, Paper No. 65-WA/HUF - 9 (1967)

22. Metz, H., McElhaney, J., and Ommaya, A.K.
A comparison of the elasticity of live, dead, and fixed brain tissue.
J.Biomechanics. (3) pp. 453-458 (1970)

23. Mays, E.T.
Bursting Injuries of the Liver.
Arch.Surg. 93:92, (1966)

24. Nahum, A.M., Gadd, C.W., Schneider, D.C. and Madeira, R.G.
Tolerances of superficial soft tissues to injury.
J.Trauma, 12 (12): 1044-1052 (1973)

25. Ommaya, A.K.
Mechanical properties of the nervous system.
J.Biomechanics. 1: pp. 127-138 (1968)

26. Ridge, M.D., and Wright, V.
The rheology of the skin. A bioengineering study of the mechanical properties of human skin in relation to its structure.
Brit.J.Dermatol. 77: 639-49 (1965)

27. Ridge, M.D. and Wright, V.
Mechanical properties of the skin: a bioengineering study of skin structure.
J.Appl.Physiol. 21(5) : 1602-1606 (1965)

28. Slatis, D.
Injuries in Fatal Traffic Accidents.
Acta Chirur.Scand.Supp. 297 (1962)

29. Snyder, R.G.
Human impact tolerance.
1970 International Automobile Safety Conference Compendium. pp.712-756

30. Tonge, J.I. et al.
Traffic Crash Fatalities: Injury Patterns and Other Factors.
Med.J.Aust. 2:5: (1972)

31. Veronda, D.R.ʹ and Westmann, R.A.
Mechanical characterization of skin-finite deformations.
J.Biomechanics (3): 111-124

32. von Gierke, H.E., Oestreicher, H.L., Franke, E.D., Parrack, H.O. and von Wittern, W.W.
Physics of vibration in living tissues.
J.Appl.Physiol. pp. 886-900