ANATOMY, INJURY FREQUENCY, BIOMECHANICS, AND HUMAN TOLERANCES

NCSS PROJECT
LITERATURE REVIEW

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by

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16. Abstract

The purpose of this literature review was to determine areas of automotive injury information that may add to knowledge of injury type, frequency, severity, and cause. This paper is a review of the literature concentrating on the period between 1965 and present. Literature on car, van, or light truck occupants has been reviewed for injury frequencies, types, and locations. Current experimental biomechanical articles are also included. A search was made for descriptions of injury frequency, restraint effectiveness, and the causes of specific injuries. Medical and engineering journals, texts, and books were reviewed. For convenience, this report is divided into sections by body region with an overview introduction on the anatomy of the specific region.

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INTRODUCTION

The National Crash Severity Study (NCSS) is producing a sample of passenger car crash data that are expected to provide better estimates of the extent and type of injuries and crashes than have been available in the United States heretofore. The purpose of this literature review is to determine areas of automotive injury information the NCSS data may most profitably add to our knowledge of injury type, frequency, severity, and cause.

This review is primarily concentrated on the period between 1965 and the present. Literature on car, van, or light truck occupants has been reviewed for injury frequencies, types and locations. Current experimental biomechanical articles are also included.

A search was made for descriptions of injury, frequency, restraint effectiveness, and the causes of specific injuries. Medical and engineering journals, texts and books, as well as all entries in the HSRI library on specific body areas (e.g., lower extremities) were reviewed. With regard to lower extremities, for example, there were initially about 250 references; by review of titles and subject content on the acquisition cards these were reduced to 125. However, as these articles were reviewed, additional references were found in their bibliographies, bringing the total hard copy reviewed close to 150 for this body region alone.

Complications in the literature were found, decreasing the chances of meaningful data comparisons among reports. For example, some authors place the pelvis with the lower extremity, a practice followed here. Some separated the pelvis (and associated organs) from the lower extremity, whereas others placed the pelvis with the abdomen. Some reports consider the knee area separately; others included the pelvis with the thigh.

A major problem with the medical literature on motor vehicle injuries is that many articles, although their titles are enticing, are concerned with treatment plans, associated medical problems and complications, and/or case histories of a very specific type of injury. There is usually little crash information contained within any of these articles. A typical crash description might read: "The patient...was an occupant of a car that hit a tree at high speed." Needless to say, such "crash data" do not add much to our understanding.

Biomechanics research laboratory data on human tolerance are generally very specific in terms of the imposed impact conditions, the body region impacted, and the subject kinematics. However, the test conditions may not be totally representative of field conditions, and may only consider a portion of the overall sequence of events in a real crash. Biomechanics research on injury is further restricted by the use of surrogates of the living human (cadavers and animals) as models to study the mechanics of trauma. Often the number of subjects tested in a particular study is small. The lack of large data samples is counteracted somewhat by the well-defined test conditions and the degree of control of the mechanical variables during a test.

Analysis of the accident data in the NCSS program is expected to bridge the gap between past field program data and laboratory experimentation when appropriate data are available. Crash severity is being measured by computer analysis (the CRASH-2 Program). Injury data are generally only obtained from qualified medical sources. This information, combined with a careful implementation of a sampling plan, should provide a better bridge between biomechanics, injuries, and injury causation than has been previously available.

Whenever possible, articles using the Abbreviated Injury Scale (AIS)[1] were chosen. Although relatively new, this injury scale is useful for international categorization and standardization of injuries for more meaningful comparisons between independent research studies.

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[1]The AIS Dictionary may be obtained from the American Association for Automotive Medicine, P.O. Box 222, Morton Grove, Illinois 60053.

This injury scale is related to injury severity: 0=No Injury; 1=Minor; 2=Moderate; 3=Serious; 4=Severe; 5=Critical; 6=Fatal (non-survival).

Subsequent sections within this report are divided into six major body regions. These are:

1. Head/Face
2. Neck/Throat
3. Thorax
4. Abdomen
5. Vertebral Column
6. Extremities

For each body region the material is further divided into a discussion of the regional anatomy, the present knowledge of injury frequency and extent, knowledge of human tolerances, and recommendations for further study.

-- THE HEAD AND FACE --

Anatomy:

The skull can easily be divided into two separate areas, the calvarium (brain case) and the facial area. The bones of the face include not only the upper and lower jaws, nasal and cheek bones, but bones of the forehead and of the orbit as well. Overlying the facial bones are the muscles of facial expression, major arteries, and nerves supplying these muscles. In general, facial bone injury is not a cause of fatality although obstruction of the airway by a displaced mandibular (lower jaw) fracture can have serious consequences. Because the facial bones of the cheeks and of the nasal area are hollow, and contain highly vascularized tissue, fracturing of these bones may cause hemorrhaging into the nose and throat which may lead to obstruction of the airway.

The brain is fairly well protected by the calvarium and by cerebral-spinal fluid which surrounds it. Tough protective membranes (the meninges) and their associated blood vessels line the inner aspect of the cranial cavity . Blunt trauma to the calvarium can, if sufficient force is applied, cause brain injury. Many of the detailed mechanisms of brain injury have been, and are being researched by a variety of investigators.

Injury Frequency, Causes of Injuries, Restraint Effectiveness:

Many authors have reported that injuries to the head are the most frequent causes of fatalities in traffic accidents. These data from reviews of hospital records and autopsy reports confirm each other internationally (Mackay; Ryan; Perry and McClellan; Kihlberg and Gensler; Grattan; Mackay et al.; Hayd).

In mass data reports on serious motor vehicle crash victims, trauma to the head is the leading cause of serious injury and death (Hossack;

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Tonge et al.; Huelke et al.; Ryan). The German Motor Traffic Insurers report indicates severe, dangerous, or fatal injuries occur twice as frequently in the head areas as do similar AIS-level injuries in the chest. Ryan reported that head (and neck) injuries are sustained most often on the windshield, door, or header area.

Lap-shoulder belts significantly reduce the frequency of severe or fatal head injury by 70%-80% (Huelke et al.). Danner reported that safety belts reduce the severity of head injury in side collisions. Bourret et al. found major head injuries were reduced by belts in all crash types. When a lap-shoulder belted occupant fatality occurs, head injuries are usually the cause of death, often in association with serious or fatal chest trauma. Recent data seems to be lacking regarding the causes of the more serious and fatal head injuries. Mackay ('72) reviewed a series of 133 serious injury and fatal crashes involving 209 unrestrained front seat occupants. He found that for fatal head and face injuries the effectiveness of the lap-shoulder belt was 33% and for the air bag an estimated 22%. For the severe head and face injuries the air bag effectiveness was 48%, with lap-shoulder belt effectiveness being at 58%. Mackay found for both drivers and passengers the overall effectiveness for the seriously injured occupants was 34% for air bags and 44% for the lap-shoulder belts. He questioned the effectiveness of air bags because of intrusion into the passenger compartment. His data also indicates a decreasing effectiveness for both types of restraint systems with increasing injury severity. Conventional three-point belts prevent at least 55% of the serious and fatal injuries to front seat occupants (Backstrom et al.; Bohlin et al.; and Tarriere).

Human Tolerances:

The tolerances of the head/face to impact forces can be categorized according to the tolerance of fractures of the:

a) skull (calvarium)

b) facial bones

c) brain

Such divisions are necessary because of wide variations in structural and/or material properties represented in each category. Skull fracture is the most thoroughly researched category and the best understood, while facial bone fracture is the least studied category and brain injury the least understood category.

Skull Fracture. The structural features of the upper portion of the calvarium resemble a reasonably uniform layered shell structure. Such a structure can exhibit three identifiable modes of failure, all related to load distribution. They are:

a) Depressed features which can exhibit a punch-through of the layers of the skull. (Localized loading with less than 3/4 sq. in. area.)

b) Comminuted-depressed fractures which exhibit a local inward bending collapse of the skull structure. (Loading with less than 2 sq. in. area.)

c) Linear fractures which exhibit undisplaced cracks through the skull structure and which originate away from, and propagate towards, the point of loading. (Distributed loading with greater than 2 sq. mi. area.)

While fractures of the skull are not necessarily serious in and of themselves, any loss of structural integrity of the skull, because of fractures, can pose a serious injury threat to the brain. Depressed fractures may occur at load and energy levels that would not produce dangerously high head accelerations, and yet, because of the threat of penetration into the brain, localized loads which produce this type of skull fracture may be avoided through appropriate interior design of the vehicle occupant compartment.

Facial Bone Fracture. Research on the fracture of facial bones has concentrated primarily upon local loading (flat circular, or narrow rectangular impactors) of the individual bones. The loads determined to cause such fractures are considerably lower (two to three times) than those associated with skull fracture. Distributed loading to the face (such as a padded instrument panel) has been shown effective in

minimizing facial bone fractures in one series of laboratory tests (Hodgson et al., '65; Daniel and Patrick).

Brain Injury Tolerance. In addition to injuries to the brain caused by a decrease in skull structural integrity through direct impact, there are a variety of brain injury mechanisms which are thought to be possible. Translational and rotational motions of the head, either by direct impact to the head or by impact to other regions of the body resulting in violent head motions, have been related to brain injury by various researchers (Hirsh and Ommaya; Hodgson et al., '70; Unterharnscheidt; Gennarelli et al.). Delicate brain and spinal cord structures are very difficult to characterize in a mechanical sense. Most studies of brain injury mechanisms have been conducted with experimental animals and the results have been extrapolated to man (Unterharnscheidt; Gennarelli et al.). This technique raises some serious questions about the applicability of quantitative values of injury criteria to the human brain. In the case of short duration direct impact to the head, often associated with linear skull fracture(s), the translational acceleration theory of brain injury, which is currently represented by the Head Injury Criteria (HIC) of FMVSS 208, would appear to be a conservative quantitative criterion (HIC < 1000).

Analysis of mechanical factors, that may lead to brain injury, is extremely difficult even in the laboratory setting. Thus, the possibility of obtaining complete biomechanics information on head injury from accident investigation would appear to be remote. This is complicated by the fact that many of the sublethal brain injuries are never actually seen by the physicians, since only in cases where it is necessary is the brain exposed for surgical treatment. Thus, many of the brain injuries which are produced in biomechanics experiments are not routinely viewed in medical practice for many can only be examined at autopsy, which is relatively infrequent.

Recommendations:

The biomechanics of most skull fractures is relatively well understood. Therefore NCSS data can better define the contact areas that are the sources of these injuries, as well as the conditions under which these injuries are sustained. The NCSS data should also be useful in determining the frequency of skull fractures and of facial bone fractures.

Accident investigation continues to be of benefit in guiding biomechanics research by documenting interior contact points and estimating vehicle crash conditions. It would not appear, however, that detailed occupant head impact data related to closed head injury (brain) can be obtained from conventional detailed accident investigations due to an inability to precisely define actual occupant dynamics, (contact force, magnitudes, and head accelerations) associated with this type of trauma.

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-- THE NECK AND THROAT --

Anatomy:

The neck is that area of the body that extends from the lower
portion of the skull and the lower jaw line, down to the area of the
clavicle (collar bone). Posteriorly in the neck are seven cervical
vertebrae surrounded by very heavy posterior cervical muscles.
Anterior, and quite prominent, is the larynx (voice box) which is a
cartilagenous inclosure around the air passageway to the lungs,
consisting of two major cartilages. The large thyroid cartilage is "V"
shaped, the base of the "V" being the thyroid prominence (Adams apple).
Beneath it is the circular cricoid cartilage that attaches to the
thyroid cartilage above and to the trachea below. Cartilage has a very
low tolerance to impact and can be relatively easily injured and may
occlude the airway. Fortunately, laryngeal impacts in automobile
accidents are infrequent. Laterally in the neck there are muscles which
cover the major blood vessels passing to and from the brain and facial
structures on each side. These, the carotid arteries and internal
jugular veins are usually not traumatized by blunt impact, but rather by
penetrating injuries--infrequent in vehicle crashes.

In the neck there are two major nerve networks, the cervical and
brachial plexes, both found on each side of the neck. The cervical
plexus supplies some of the deeper neck muscles, and the overlying skin.
The brachial plexus, on the other hand, supplies the upper extremity
(muscles, joints, and skin), and cervical injuries may involve the
cervical spinal cord or one or more of these brachial plexus nerves.

Injury Frequency, Causes of Injuries,
Restraint Effectiveness:

Cervical spine details are presented in the section on "The
Vertebral Column."

Although there have been a spattering of articles on laryngeal trauma in the clinical literature (Curtin et al.; Nahum and Siegel; Nahum; Bhagat; Fitz-Hugh et al.; and Olson), there are no data available on the frequency of injuries to the anterior neck (throat) structures. Most data on the types of injuries to the larynx are clinical case reviews, with most authors agreeing that such injuries are due to blunt trauma to the throat from impacts to the steering wheel rim or the upper edge of the instrument panel.

Automotive crashes may produce anterior throat impacts causing nerve damage with subsequent voice weakening or loss, edema with partial or complete airway obstruction, or extensive crushing of the laryngeal cartilages with loss of airway patency. The frequency of such injuries must be low, for neck injury data always emphasizes cervical spine and/ or associated muscle injuries (cervical sprain-"whiplash"). The lap-shoulder belt can prevent anterior throat impacts (Butler and Moser). An autopsy incidence of 9.2% injury to the anterior throat structures in 500 car drivers and passengers has been reported, but most of these car occupants (65%) died of head and/or chest injuries (Tonge et al., Australia).

Human Tolerances

Nahum et al. ('68) tested intact embalmed cadavers with loads of 200-250 lbs., producing marginal fractures of the thyroid cartilage; cricoid cartilages fractured at loads of 175-225 lbs. Gadd et al., using unembalmed cadavers, showed marginal fractures of the laryngeal cartilages at 90-100 lbs. It is believed that the stiffening of the embalmed tissues about the laryngeal area allowed the larynx to absorb more of the energy from the impact, thus exhibiting injury at the lower loads.

Most recently Melvin et al. studied the fracture load level of the larynges removed from cadavers. For the thyroid cartilage, the mean dynamic fracture load was 40.6 lbs., and for cricoid cartilage, 55.5 lbs., significantly lower than previous studies. The mean load for imminent structural collapse of the larynx was found to be 100 lbs.

Recommendations:

To specifically identify the frequency of anterior neck injuries
and their severity, accurate data should be recorded in NCSS forms.
Without such precise information throat injury frequency and severity
will remain poorly understood. Human tolerance data on the laryngeal
cartilages are apparently available for fracture levels, but no
information is available on the forces needed for the production of
nerve damage or edematous (swelling) changes in the mucosal lining of
the larynx.

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-- THE THORAX --

Anatomy:

The thorax begins at the base of the neck at the level of the first rib, and extends down to the lower rib margins and the respiratory diaphragm which separates the thoracic contents from the abdominal cavity. The bony thorax consists of the twelve pairs of ribs, the sternum (breast bone) in front, and the twelve thoracic vertebrae posteriorly. Outside of the bony thorax are a series of muscles that attach to the upper extremity. Filling in the rib interspaces are the very flat thin intercostal muscles. Importantly, running along the lower edges of the ribs and in the intercostal muscles are the intercostal arteries, veins, and nerves, which can cause severe pain and/or hemorrhaging if rib fracture segments perforate these blood vessels and contuse the nerves.

The thoracic cavity is oval in shape, being narrower from front to back than from side to side. At the mid-thoracic level (from top to bottom) the deep side of the sternum is but a few inches from the anterior side of the vertebrae.

The thorax is divided into three cavities: one cavity for each of the lungs on the right and left sides, and the mediastinum, a group of centrally located structures very close to the mid-line. These mediastinal structures include the heart, the great vessels of the heart, the trachea (windpipe), and the esophagus--the passageway from the throat to the stomach. Also in the mediastinum are major nerves, as well as the main artery of the body (the aorta). There is a close adherence of the lung cavity lining (the pleura); thus rib fractures can easily tear the pleura, allowing free blood or even air to enter the lung cavity (pleura cavity) causing pneumo- or hemothorax which, if excessive, can significantly reduce the respiratory capacity of an injured individual. All trauma to the mediastinal structures are at the severe, serious, critical, or the fatal level of severity.

Injury Frequency, Causes of Injuries,
Restraint Effectiveness:

Injuries to the chest area are of significant concern because of
the life-sustaining organs, particularly the heart, great vessels and
lungs, housed within.

Although soft-tissue injuries of the chest are common, the more
severe or fatal injuries almost always involve the cardio-pulmonary
systems. In a study of 453 car occupant fatalities, Tonge et
al. (Australia) found that about 50% had rib fractures, with some level
of heart injuries occurring in about 2% of drivers and 11% of
passengers. Lung contusions or lacerations were noted in 37% of the
fatalities with major vessel injury reported in 10%. Injury to the
mediastinal structures other than heart, aorta, and great vessels was
noted in about 15% of these victims. These frequencies were confirmed
in another Australian study of 500 car fatalities by Hossack.

Kemmerer et al. studied 585 traffic deaths, including pedestrians,
and found that 294 (50%) had significant thoracic injuries, with 133
(23%) dying primarily as a result of thoracic injuries.

Hardwick compared chest injuries in seat-belted and unrestrained
occupants in a Canadian hospital study. He found that there was a drop
in hospital admissions by more than 50% for belted occupants, and that
those belted occupants hospitalized with chest injuries had a decrease
of 75% in the length of the hospitalization compared to those unbelted.

Lap-shoulder belts have been reported to reduce serious thoracic
injury level by about 26% to 64%, depending on the data base used, and
to prevent fatalities by 33% (Huelke and Lawson et al.). In lap-
shoulder belted occupant fatalities, the chest is still frequently the
body area involved, often in association with the head (Huelke et al.).
Mackay in his series of 133 serious and fatal crashes found that for
thoracic injuries the effectiveness was 33% for both air bags and lap-
shoulder belts. For severe thoracic injuries, the air bag was 14%
effective and the lap-shoulder belt 19% effective.

Human Tolerances:

The thorax has received a great deal of attention in biomechanics research during the past five years. A large portion of this research has been concerned with mid-sagittal plane frontal impacts, centered on the sternum, with a flat circular impactor six inches in diameter. The work of Nahum et al. and the work of Stalnaker and Mohan has been summarized in an analysis by Neathery in which chest impact response and injury data from the previous studies were scaled to produce recommended response and injury levels for the driving population. Such specialized testing has led to an improved understanding of some thoracic response and injury problems, but much work remains to produce an understanding of impact tolerance and injury mechanisms in other directions of loading.

Side impact tolerance of the thorax has received limited attention, both in local loading experiments (Stalnaker et al.) similar in nature to the mid-saggital plane frontal experiments mentioned above, and in whole-body side impacts with distributed loading on the thorax (Melvin et al.).

Additional data on thoracic injury and tolerance can be obtained from the analysis of shoulder harness loading of the thorax during restraint systems tests with cadavers. Eppinger analyzed the data from such tests to produce a statistically based estimate of belt webbing loads that would produce a minimum number of rib fractures in the driving population.

Injury criteria relating thoracic response levels to resulting injuries have centered on either measurement of spinal accelerations or a simple measure of rib cage deflection. Neither measure has been biomechanically validated for multidirectional loading or for various types of impacting surfaces, shapes, and properties. Recent work reported by Robbins et al. has addressed this problem through the use of multi-accelerometer array mounted at various points on the rib cage of human surrogates to more completely describe the global response of the rib cage. The method also utilizes statistical techniques to analyze and characterize the responses of the various accelerometers under a variety of test conditions in order to determine a predictive function

which will allow the assessment of injury level (AIS) from the accelerometer-based data.

Throughout the above studies, the ability of the rib cage to carry load without rib fracture appears to be affected strongly by the age of the cadaver test subjects. The number of rib fractures produced in sled tests with cadavers is thought to be greater than would be expected from actual crashes. Since most cadavers are of advanced age, this effect may be due partly to their age and partly due to a lack of realism of the cadaver thorax as a surrogate of the living human. This problem has not been adequately resolved.

Recommendations:

Detailed and accurate data on specific injury severity, injury types, and impact locations are needed for design changes and regulatory activity.

The analysis of the NCSS data can very usefully be directed at answering specific questions with respect to occupant age, direction of loading, type of loading, and their effects on thoracic injury. A concerted effort in studying this body region, which is of critical interest in advanced restraint system evaluation, will likely be very useful as an aid to biomechanics research.

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-- THE ABDOMEN --

Anatomy:

The abdomen extends from the respiratory diaphragm, approximately at the level of the lower rib cage, down into the area surrounded by the bony pelvis, the pelvic cavity. The abdominal-pelvic cavities are continuous and in this report will be considered as a single region. The abdominal wall is primarily made up of very flat muscles anteriorly and laterally. Posteriorly there are the five lumbar vertebrae and their relatively large and heavy associated musculature.

Within the abdominal cavity there are hollow organs, parts of organ systems, as well as solid organs. The solid organs are typified by the liver and spleen. The hollow organs are the stomach, intestine, and colon. Fairly well protected by the bony pelvis is the urinary bladder, the rectum, and in the female, the uterus. It must be remembered, however, that loops of intestines hang down into the pelvic area and therefore can be traumatized by pelvic or low abdominal impacts. On the left posterio-lateral side is the descending and sigmoid colon; on the right side is the ascending colon. These can also be injured by abdominal or pelvic impacts.

Major blood vessels, the abdominal aorta and inferior vena cava, pass along the anterior side of the lumbar vertebrae with large, multiple branches supplying all of the organs within the abdominal and pelvic cavities.

The liver, a major abdominal organ, is housed beneath the diaphragm and is almost completely under the lower right rib cage. Because of its location an impact to the lower thoracic area is usually the main mechanism for blunt liver injury.

Abdominal organs are very susceptible to trauma because they are often either fluid filled or gas filled, which causes distention of

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their walls. The spleen and liver apparently have a relatively low tolerance to impact as evidenced by their high frequency of injury.

Injury Frequency, Causes of Injuries, Restraint Effectiveness:

All authors who have tabulated data on blunt abdominal injuries, whether from a series of clinical cases at surgery or from a series of autopsies, agree that the liver and spleen are the most frequently traumatized organs of the body. All of the other organs of the abdomen have been reported to be injured to some level but none as frequent as the liver and spleen (Divincenti et al.; Perry; Ryan; Walt and Grifka).

Hossack (Australia) found in his study of 500 drivers and passenger car occupant autopsies that approximately 18% had ruptured livers and 10% had ruptured spleens. Damage to other internal organs was less frequently noted. Tonge et al. (Australia), in their study of fatal car drivers and passengers, found that approximately one in four had liver or splenic injuries, with 10% having one or both kidneys injured. They also found approximately 15% of the individuals having retroperitoneal hemorrhage.

In the German Motor Traffic Insurers study on 28,936 car crashes, approximately 0.6% of the drivers had severe or dangerous abdominal injuries and 0.2% were killed from abdominal impacts. For passengers the severe to dangerous abdominal injuries were recorded at 0.7% level, with fatalities at 0.3%. The majority of these drivers and front passengers (94%) were uninjured in the abdominal area.

Grant (England) studied 1800 vehicle occupant casualties who were treated at one large accident hospital. In his study he found that abdominal injuries occurred in 7.8% of these individuals. Neither the level of injury severity nor the type of abdominal injury was indicated.

Although injuries to the lumbar vertebral spine occur in the unrestrained occupant, most of the sporadic, anecdotal reports in the medical literature on lumbar spine fractures or dislocations have been concerned with the injuries to lap-belted occupants. The literature on this subject is best summarized in reports by Huelke and Kaufer, and Huelke and Snyder.

Lap-shoulder belt effectiveness in reducing the more severe or fatal lower torso injuries has been documented by Huelke et al. Using CPIR data they found a 61% reduction in the more serious lower torso injuries in frontal crashes (compared to the unrestrained) and a 67% reduction in rollover crashes. Fatalities were less often seen in the lap-shoulder belted in frontal (29%) and rollover (49%) crashes.

Human Tolerances:

The abdomen has received very limited attention in biomechanics research. This is partly due to the difficulty in describing the mechanical behavior of the highly deformable, very mobile organs in the abdomen, and due to greater concern for the prevention of injury to more critical organs of the body (brain, spinal cord, heart, etc.).

Stalnaker et al. have presented extensive data on animal experiments which were scaled by means of dimensional analysis to estimate human abdominal tolerance. The nature of the loading surface (shape and stiffness) has a great influence upon the reaction of the abdomen to load. Melvin et al. conducted direct impact experiments on individual abdominal organs (liver and kidney) to obtain more consistent data on organ injury. They found the organs to be strain rate sensitive, especially the liver which was found to fail due to dynamic pressures generated in the tissue during impact.

The apparent situation in abdominal trauma is that the internal organs are trapped by the intruding structure and locally compressed. If the organ is able to move out of the way of the intruding structure very little injury will occur to them, but excessive movement may disrupt their attachments and blood supply. Thus, the mobility of the abdominal organs add a degree of variability in the occurrence of abdominal injury that is difficult to account for in laboratory testing. In addition there may be organ to organ impact causing injury somewhat away from the location of force application. Hollow organs may rupture more easily if they are distended by gases or fluids.

Recommendations:

Because there are no accurate data on crashes in the United States for injury frequency, injury severity, or types of abdominal injuries, accurate data are needed.

Data are sufficient to show the injury reduction potential of lap-shoulder belts in the frontal and rollover crash.

Probably no other single body region has such lack of human tolerance data as does the lower torso, especially the abdominal organs. Significant biomedical/biomechanical research is urgently needed for any future motor vehicle occupant safety standards.

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-- THE VERTEBRAL COLUMN --

Anatomy:

The vertebral column is anatomically divided into the cervical, thoracic, lumbar, and sacral regions. There are seven cervical vetebrae, twelve thoracic, and five lumbar vertebrae, with four or five sacral vertebrae which, in normal development, fuse to one another to form a fairly large hand-sized bone that joins with the pelvic bones posteriorly. Extending from the lower part of the sacrum is the small finger-like coccyx bone which is rarely injured in vehicle crashes.

The seven cervical vertebrae are small and delicate in comparison to all others. Like all other vertebrae they have ligaments that attach to them, with intervertebral discs between each and every one of the cervical, and all other vertebrae, except between the sacrum and coccyx and between the first and second cervical vertebrae.

The first vertebra articulates with the base of the skull and with the second cervical vertebra below. These two vertebrae C1 (altas) and C2 (axis) are uniquely different from all other vertebrae. Whereas all other vertebrae have a block of bone, the vertebral bodies, located anteriorly, the first cervical vertebrae does not have a body. The second vertebra, on the other hand, does have a body and protruding upward from it is a small finger-like process, the odontoid or dens process, for the pivoting motion of the head.

All vertebrae are interconnected by ligaments that join one bone to another as well as very long ligaments that extend the entire length of the vertebral column. Heavy musculature is found on the posterior and lateral sides of the vertebrae to give the characteristic actions of flexion (forward bending), extension (rearward bending), or side to side bending, as well as some rotation. Rotation is best seen in the cervical area for this is a region of the body that has the highest mobility. Wherever there is high mobility in the body that body region is more susceptible to injury.

Severe cervical injuries can be devastating, for the spinal cord runs behind the vertebral body, surrounded by bone on its sides. Fractures, and/or dislocations, can be severe in terms of debilitation. If it involves the spinal cord, nerve paralysis is usually irreversible, and is the sequellae to the injury.

The twelve thoracic vertebrae are larger than those in the cervical area and have ribs attaching to them. Severe thoracic vertebral injury is not frequently seen because the ribs tend to be a major stabilizing factor. Vertebral column injuries are more often found between the junction of the thoracic and cervical levels or at the thoracic-lumbar junction.

In the lumbar area there are five fairly large vertebrae, and, because there is not the stabilizing influence of the ribs, bending, twisting and rotation movements are significant in this area. It is in the area of the upper lumbar vertebrae that the spinal cord ends, terminating in multiple nerve filaments to supply the pelvic area and lower extremities. Thus injuries in the lumbar vertebrae, fracture or dislocation, may cause spinal cord injury or involvement of the terminal nerve filaments.

The sacrum fits posteriorly between the right and left sides of the pelvis via the sacroiliac joints. Only infrequently are the sacrum or the sacroiliac joints involved in pelvic injuries.

Injury Frequency, Causes of Injuries,
Restraint Effectiveness:

Cervical Spine. The literature on injuries to the cervical spine and associated structures is extensive. From the cervical sprain syndrome (whiplash) to the potentially devastating fracture-dislocations, the medical literature is a plethora of clinical case data on treatment plans, and detailed case histories. There are a variety of neck injuries, the majority being of the ache and pain--the whiplash--variety, due to overstretching of the muscles and ligaments about the cervical vertebrae.

The more serious-to-fatal injuries are fractures or fracture-dislocations with or without spinal cord involvement. To speak of a

"broken neck" is a misnomer, for there are many types of neck fractures (Braakman and Penning; Babcock; Katten; Portnoy et al.). Over-bending fractures--hyperflexion (forward bending) or hyperextension (rearward bending)--each may be of one or two types, associated with compression forces (compressive hyperflexion fracture) or with tensile forces (distractive hyperflexion fracture). In addition there may be rotatory forces involved, with each of the above. Lateral bending fractures are another type, producing compression of vertebral structures on the side of the bending with tensile forces separating similar structures on the opposite side.

At the upper cervical level (C-1 to C-2) specific fractures, different from those found lower down in the neck, are noted. Often these are referred to as hangman's fractures (Schneider et al.). Thus there are many types of fractures or fracture-dislocations, each with its own specific identifying characteristics.

Most neck fractures are due to excessive bending with force applications through the neck via the torso mass after the head has decelerated. However, Huelke et al. ('78) reported on neck fractures and fracture-dislocations without head impact. In another study (Huelke et al., '77) using the CPIR file no severe-to-fatal neck injuries were found in lap-shoulder belted occupants involved in frontal or rollover crashes.

Meaningful reports on cervical spine injury are limited. There are no frequency data for the various types of neck fractures or fracture-dislocations. No reports were found indicating that direct impact to the neck causes fractures in car crashes.

The extensive German Motor Traffic Insurers report on 28,936 drivers and 14,954 front seat passengers in crashes indicates that severe to fatal cervical spine injuries occur in 0.4% each for drivers and for passengers. It was indicated that more than 50% of all cervical injuries were in the rear-end crash, but that the highest risk of severe and fatal cervical injuries is incurred in frontal collisions.

Alker et al. reviewed postmortem x-rays of 146 consecutive traffic accident autopsies (probably including pedestrians) and found 21.2% had cervical spine injuries.

Tonge et al. (Australia) found cervical fractures or dislocations in 10.9% of autopsied drivers and 16.7% of passengers. Hossack (Australia) reviewed 500 drivers and passengers killed in crashes. He found that 7% of these autopsied victims had cervical fractures with cord damage. In this study about two-thirds died due to head or chest injuries, or a combination of the two.

States et al. indicates that "whiplash" injuries tend to be underreported. Whiplash injuries usually are associated with the rear-end crash; however, cervical sprains and pains have been noted in lap-shoulder belted occupants in frontal crashes, in unrestrained occupants striking the windshield (induced neck injury), or in occupants in side impacts which produce lateral neck bending. Impingement on the neck by a shoulder belt causing non-paralytic vertebral injury has been reported (Arndt).

Thoracic/Lumbar Vertebrae. Injuries to the thoracic/lumbar spine are relatively infrequent. When they do occur the injuries are usually contusions, sprains, and other less severe injuries. The fracture and dislocations of a severe, dangerous, or fatal degree are very infrequent in occurrence as indicated by data in the German Motor Traffic Insurers report, by Ryan, and by Perry and McClellan. Even at autopsy these more serious injuries are infrequently noted (Hossack; Tonge et al.). However, it has been estimated that about 5,300 spinal cord injured motor vehicle occupants, including about 2,000 fatalities, occurred in 1974. How many were car occupants is not known (Smart and Sanders).

Comprehensive literature review on lap belt related lumbar spine fractures and/or dislocations has been provided by Huelke and Kaufer, and by Huelke and Snyder. Generally, spine injuries of the more severe types are due to ejection, door impact, or occur in rollover crashes. Lap-shoulder belted occupants with thoracic/lumbar fractures are rare; only a few cases have been reported.

Human Tolerances:

It is generally useful to separate spine injury cases into direct impact loading of the spine due to contact with vehicle interior structures and indirect or inertial loading due to motions of body components which eventually transmit load to the spinal column.

Biomechanics research on the thoracic and lumbar spine has, for the most part, been focused upon vertical loading of the spine. This is due to the great interest in the aircraft pilot-ejection seat design problem. This type of loading is relatively rare in the automotive situation. Loading of the spine in the horizontal plane is much more common in automobile crashes, however very little is known quantitatively about this topic at this time. Cervical spine biomechanics research must consider both horizontal and vertical loading, since, in many crashes, the occupants can impact their heads on interior structures decelerating the head allowing the unrestrained torso to produce loading in these directions.

The state of knowledge on the quantitative biomechanics of cervical spine injury is very limited. There have been very few studies addressing the determination of the forces necessary to cause cervical spine damage due to direct loading to the neck or through direct loading of the head. This is the case for both anterior-posterior loading and for superior-inferior impacts.

The only study available at this time on superior-inferior impact loading of the cervical spine is one reported recently by Culver et al. Impact tests to eleven cadavers were conducted with a moving mass impactor. Spinal fractures were produced in many cases, but no basal skull fractures were produced. The mechanism of cervical vertebrae fractures, in the test configuration used, appeared to be the compressive forward arching of the neck (hyperextension) which placed loads on the spinous processes and connecting arches along the back of the spine. The work reported in the study was intended as a preliminary study and much further work is needed to fully explore the various mechanisms of cervical spine damage found in superior-inferior loading cases.

The work of Mertz and Patrick has been the only study to date to suggest human tolerance values for the cervical spine loading due to indirect (inertial) loading. Based on human volunteer and cadaver sled tests, they found that the resultant bending moment about the occipital condyles was an excellent indicator of neck strength. Although this work was done some years ago, there has been no subsequent research which has indicated larger tolerable values of neck loading.

Recommendations:

Neck fracture and fracture-dislocation frequency data, as to type of injury, cause of, and type of vehicle crash, is required. Only detailed medical and x-ray reports, as well as individual x-ray studies by researchers, will give the necessary information. Human tolerance data are definitely needed. Due to the disastrous, debilitating effects of severe neck injury (quadraplegia), a long term research program to quantify the various types of neck fractures and fracture-dislocations is strongly recommended.

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-- THE EXTREMITIES --

<u>Anatomy</u>:

The upper extremity includes the areas of the shoulder girdle, arm, forearm, wrist and hands, the bones, articulations, muscles and associated neurovascular structures. The bones of the shoulder girdle are the scapula (shoulder blade) and clavicle (collar bone), articulating with each other at the shoulder point, the acromioclavicular joint (shoulder point). The arm extends from the shoulder to the elbow; the forearm, from the elbow to the wrist. There is one bone in the arm, the humerus, surrounded by muscles for shoulder and elbow movements. Along the inner (medial) side of the arm pass all of the blood vessels to and from the distal structures of the forearm and wrist and hand. Within the forearm are two bones, the radius and ulna, and the overlying muscles for wrist, hand and finger movements. The wrist consists of eight small bones (carpals) articulating with the lower end of the forearm and with the five bones (metacarpals) of the hand. At the ends of these hand bones (knuckles) are the articulations of the bones of the fingers.

The lower extremity includes the bony pelvis and the muscles that attach thereon, the thigh, leg, ankle and foot, the muscles, nerves and blood vessels of the area, and the interconnecting joints--the hip, knee, ankle and foot articulations. For clarification the thigh extends from the hip to the knee; the leg, between the knee and ankle. In the thigh, there is one bone (the femur) surrounded on all sides by heavy musculature. Above, the femur joins with the pelvis in a ball and socket type of articulation (hip joint). In the leg, the tibia (shin) is the main supporting bone, with the thinner bone (the fibula) found on the lateral side. The knee joint is formed by an articulation between the femur and tibia. At the ankle joint the tibia and fibula form a mortice with an ankle bone (the talus) to provide joint motion

characteristic of ankle movement. Below this there are important joints between the seven ankle bones and between several of these and the bones of the foot.

Bones are interconnected by fibrous tissue--the joint ligaments--which if injured by stretching and tearing causes sprains and joint instability. These ligaments generally surround the joint areas. Yet in the hip, knee and some ankle bone articulations there are ligaments within the joint, characterized by the cruciate ligaments within the knee joint.

Injury Frequency, Causes of Injuries, Restraint Effectiveness:

There are no accurate data on the number, frequency, or extent of extremity injuries related to motor vehicle crashes. Although there are many case descriptions of extremity injuries in the medical literature, they are too numerous to list and collectively would add little to the present review.

An extensive study by the German Motor Insurer's on 28,936 drivers and 14,954 front seat passengers indicates that lower extremity injuries are infrequent (thigh: 0.5%; knee: 0.4%; leg: 0.3%; foot: 0.1% to 0.2%). In the upper extremity severe injuries are even less frequent (shoulder: 0.1%; arm: 0.1% to 0.4%; forearm: 0.1% to 0.2%; and hand: 0.1%).

It has been shown by Danner (Germany) that 1,178 occupants who were struck at the opposite side of the car, only 2% had a severe or greater injury to the upper and/or lower extremities. Of these more severe injuries the major injury was a fracture of one of the long bones of the extremities. There were no fatal extremity lesions in these occupants.

In 1968 Nahum et al. reviewed the data of 290 crashes. These accidents involved at least one occupant who sustained an injury of moderate (non-dangerous) or dangerous (non-fatal) degree. These accidents involved 239 car occupants with a total of 496 significant injuries. Of these, 10% were of the upper extremity and 13% in the lower limb. Half of the upper limb injuries and 60% of the lower extremity injuries were sustained on the instrument panel. An additional 20% of the lower limb injuries were produced from the floor

or toepan area. Of the lower extremity injuries only 9 were at the dangerous level and two were fatalities. Most of these serious injuries were at impact speeds above 30 mph.

Nagel and States, in a study of 74 accidents, found 57 of the 153 people injured had 80 knee injuries with 69 of these injuries resulting from impact with the dashboard. Of these, 51 had "mild injuries," 10 had moderate injuries (laceration or simple patellar fracture), and 8 had severe injuries (laceration or fracture into the joint or tearing of the knee ligaments). The authors concluded that degenerative arthritis will develop in the more seriously injured knees. Seat belts do help for of the 15 occupants who were belted, only one had a serious knee injury.

Patients who were admitted to St. Vincent's Hospital (Sydney, Australia) during 1966-1968 were the basis of a report by Nash. Of 114 car occupants, 47% had some leg injury; but the severity of these injuries was not indicated.

Ryan reported on 218 car and truck crashes (1,114 occupants) from the city of Adelaide (Australia). Of these there were 263 with lower limb injuries (excluding the pelvis, which he placed with the spine injury data). Most (246) had minor lower extremity injuries. The instrument panel accounted for more than one-half of these lower extremity injuries.

Perry and McClellan reported on autopsy data on 64 automobile occupants. There were 27 pelvic or lower extremity fractures or major vessel injuries with two being the primary cause of death.

Goegler, in an extensive study of road casualties treated at the Heidelberg Clinic (Germany) between 1952-1958, found car driver injuries to the pelvis or lower extremities in 28% of the cases; the severity of these injuries were not indicated. Pelvic fractures in seat-belted occupants are infrequent, for there are but few anecdotal reports in the literature.

Rarely do fatal extremity injuries occur, for crash injury data hardly ever indicate deaths directly attributed to the extremities. Nagel et al. ('73) did not find any lower extremity fatalities in their

series of crashes, nor did the German Motor Traffic Insurers in a study of 28,936 car crashes.

Even when pedestrians are included, the relative infrequency of lower extremity fatalities was noted by Giraldo (Columbia, South America). In this study of 135 fatalities he had only one fatality due to fat embolism following multiple lower extremity fractures.

Huelke et al. did not find a lower limb fatality in their extensive review of the CPIR data on frontal and rollover crashes. No fatal extremity injuries were reported in a study of fatal crashes in Melbourne, Australia (Rubinstein).

At a meeting on "Impact Injury and Protection" in the late 60's, Kihlberg presented results of the ACIR Program of Cornell Aeronautical Laboratory Research into automobile collisions. Using a data base of 5,597 injured persons, tabulations and analysis of the various kinds of injuries and frequencies of multiple body areas injured were presented. The pelvis was included in the abdominal area and anything below the pelvis was considered the lower extremity. He indicated that the lower limb was involved in 50.4% of the injured occupants; severity of the lower limb injury was not indicated. Nelson found the lower extremity to be infrequently the "most severe injury" in lap-shoulder belted occupants.

As States et al. indicated, there have been many reports on injury mechanisms in the literature back to 1938. However, for the lower extremities much of the material has not been adequately and meaningfully tabulated. States et al. and Nagel et al. ('77) described a variety of lower extremity injury mechanisms and showed examples of loading of the foot-ankle complex through the floorboards with the knee impacting and locking into the instrument panel. They showed that feet entrapped by the pedals cause excessive loading at the femoral neck, as well as hip dislocation due to angle crashes with occupants impacting their hip area directly on the instrument panel.

In a 1968 article (States and States), 78 occupants who were injured in lateral impact accidents were studied. In these 74 cases there were 27 injuries to the pelvis and lower extremities; it is not

indicated whether some of these individuals had more than one injury. The eleven pelvic injuries were due to the front door or arm rest, with the majority of the lower extremity injuries from the same part of the car. The injury severity level was not indicated. These data came from a multidisciplinary accident data investigation research project at the University of Rochester. All model year cars were included with the bulk being pre-1968 model cars.

In a study of 1973 and 1974 passenger cars, Marsh et al. presented data which indicated that lap and/or lap-shoulder belted occupants have a lower frequency of injuries than do unbelted occupants. However, the injury severity was not indicated.

More recently Melvin et al. ('75) presented lower extremity injury information by a review of multidisciplinary accident investigations. They reviewed frontal crashes of passenger cars with unrestrained passengers 12 years of age or older. At the time of their review there were 13,088 cases in the CPIR file, of which there were 2,024 cases that satisfied their requirements of injuries to the lower legs and feet. There were 382 cases that had AIS 2 or greater for at least the leg or pelvis. They reviewed the original case files as well as those involving knee, femoral, or pelvic fractures for in-depth study. They then found 142 cases of interest to detail the types and location of injuries within this anatomical area. Of these 142 individuals with lower extremity injuries, the pelvis and both femurs were fractured in 2.7% of the cases, pelvis and one femur in 6.3%, fractures of only the pelvis 19.8%, of one femur 46.8%, bilateral femoral fractures 8.1%, and patellar fractures in 16.2%. It must be recalled again that the percentages shown above are based on 142 individuals who were injured. Based on 2,024 cases, the relative frequency of occurrence of these more severe injuries is very low. For example, the femoral fractures (indicated as being 46.8%) is actually at about the 3% level of occurrence in the CPIR file which, in general, reflects occupant injuries of a more severe nature than the general accident population.

Lap-shoulder belts are very effective in reducing extremity injuries. In a study of 108 lap-shoulder belted car occupants with injuries in various crash type, Mackay et al. (England) found 21 pelvic

injuries (7 at the AIS-3 level), 66 lower extremity injuries (7 at the AIS-3, and 1 at the AIS-4 level), and 34 upper extremity injuries (4 at the AIS-3 level). No pelvic injuries were due to the belt systems.

In their rollover study of 225 occupants (39 restrained) Hight et al. found only 18 with injuries of AIS-3 or greater, with only 2 fatalities. Only 4 extremities were noted in the unrestrained group and one pelvic AIS-3 injury in a lap-belted occupant.

Huelke et al. reported on frontal and rollover crashes (CPIR data) and found an 81% reduction in the more severe lower extremity injuries (AIS 3-5) in frontal collisions and a 74% reduction in rollover crashes associated with the use of lap-shoulder belts.

Huelke and Lawson presented data on injuries associated with automobile seat belts. Using multidisciplinary accident investigation data (CPIR file), they found that the pelvic area was injured in 5% of unrestrained occupants and in 9% of those wearing lap belts. Their data base included 3,845 unrestrained front seat occupants and 945 wearing lap belts. However, when the more serious injuries of AIS-3 or greater were reviewed, it was noted that 28% of those unrestrained front seat occupants had these more severe pelvic injuries as compared to 9% of those wearing a lap belt. A review of the hard copy of the actual cases indicate to the authors that in at least 7 of the belted individuals with pelvic injuries, the injuries could have been caused by objects such as the steering wheel, door or instrument panel, transmission lever, etc., either solely or in combination with the lap belt. Of those occupants with pelvic fractures, most all were in crashes in the higher speed ranges. They also concluded that the outboard seat belt angle had no relation to pelvic or lower torso injuries.

In a 1977 publication, Huelke et al. reviewed CPIR data for frontal and rollover crashes. They found that the lower extremities are injured at the AIS 3-5 level in 4.8% of the unrestrained outboard occupants in frontal crashes, and those with lap belts at a 2.4% level. Lap-shoulder belted occupants rarely had lower extremity injuries in frontal crashes, for the data indicated less than 1% occurrence of AIS 3-5 lower extremity injuries. In rollovers they found that the lower extremities were injured more often at the AIS 3-5 level, for here the unrestrained

occupant had such injuries more often (6.5%) than lap-shoulder belted occupants (1.7%).

In both frontal and rollover crashes there were no lower extremity fatalities found in the CPIR file. Also in these rollover cases lap-shoulder belts reduced the frequency of lower extremity injuries. Huelke et al. found that when ejection occurs, 10% of the unrestrained occupants have the more severe injuries. In the CPIR file no lap-shoulder belted occupant had lower extremity injury above a minor level (AIS 1). When the non-ejected occupants of rollover crashes were reviewed, the AIS 3-5 lower extremity injuries occurred in 5% of the unrestrained and in less than 2% in the lap-shoulder belted individuals, a 60% improvement.

It is obvious that the medical literature is sparse and basically non-existent in meaningful data on the injury occurrence and frequency of specific types of injuries. There is a plethora of typical medical reports of extremity injuries, but from these reports injury frequencies cannot be obtained. The reports are typically restricted to one subject area, such as a series of pelvic, hip or leg fractures, without giving the important data as to the frequency of these injuries. This is understandable, for the attending physicians who authored these reports are not versed in accident investigation, nor do they have available data for statistical analysis.

Human Tolerances:

There are no biomechanical data available on the upper extremity. No human tolerance data are available on the ankle or foot that are applicable to the automotive crash environment.

Patrick, Kroell and Mertz determined the strength of the patella/femur/pelvis complex in impacts simulating knees striking into instrument panels. Ten embalmed cadavers translated forward upon sled deceleration to impact against four lightly padded load cells. The head, chest, and each knee struck a separate load cell. They concluded that the femur was slightly more vulnerable to fracture than the patella or the pelvis, but that distinction was too small to allow confident prediction as to which bone structure would fail first. They also

concluded that a "load of 1,400 lbs. should certainly represent a reasonably conservative value for the overall injury threshold level" of this bone complex. A later study by the same investigators determined that a load of 1,950 pounds was not unreasonable.

More recent femur tolerance studies have employed stationary seated cadavers which were struck by moving impactors. Powell et al. ('75) tested the legs of nine cadavers and obtained fractures at loads ranging from 1,600 pounds to 2,970 pounds (average 2,360 pounds). Eighty percent of their legs suffered patellar fractures, 33% were condylar (the portion of the femur adjacent to the patella), and only 6.7% were to the shaft of the femur. They attributed their fracture patterns to the rigid impactor which they used; their distribution of fractures is not typical of those seen in field accidents.

Melvin et al. ('75) employed an impactor with one inch of Ensolite padding to test the femurs of fourteen stationary seated cadavers. No fractures were obtained below 3,000 pounds and it was noted that a threshold impactor momentum of 40-50 lb./sec. appeared to be necessary to cause fracture. The relatively high load levels were attributed to the exclusive use of unembalmed cadavers. All of these fractures were in the patella and in the distal third and supracondylar region of the femur.

Viano has analyzed the stress distribution in the femur due to its irregular shape. He concluded that the location and magnitude of peak femur stresses can be significantly affected by small shifts in the location of the applied load, such as moving its point of application from one condyle to the other. In addition, Viano has hypothesized that the ultimate strength of the femur should be dependent on the duration of the applied pulse.

Recent femur tolerance research has been largely based on relatively short duration knee impacts (approximately 10 ms.). If Viano is correct, such data is not directly applicable to the longer duration event of knees striking into instrument panels. Additional tolerance data based on longer duration impacts is needed.

Kramer et al. performed 209 transverse impacts against the lower legs of cadavers. His 5.7 inch diameter impact cylinder produced a 50% frequency of fracture at a force of 970 pounds; his 8.5 inch diameter cylinder produced a corresponding force of 740 pounds.

Powell et al. ('74) reported the results of rigid impacts to the knee Using seated cadavers, an impact load was applied to one flexed leg at a time by means of a striker pendulum with either a 34.3 pound (15.6 kg) or 50 pound (22.7 kg) striker head with a flat rigid impact face. The cadaver was seated in a modified barber's chair which included a back support. A total of fifteen tests on nine cadavers, of which seven were embalmed and two unembalmed, were reported. The test results were as follows:

1) Patella fractures were observed in twelve of the fifteen legs tested, often at force levels below those needed for femur fractures.

2) Condylar fractures were observed in five of the legs.

3) Shaft fractures occurred in only one of the legs.

4) Hip (pelvic and femoral neck) fractures were observed in two legs. Excluding patellar fractures, femur fractures were produced in seven of the fifteen legs at an average load of 2,250 pounds (10.04 kN) with a range of 1,600-2,812 pounds (7.1 - 12.5 kN). The patellar fractures occurred at an average load of 2,470 pounds (10.75 kN) with a range of 1,782 - 2,970 (7.9 -1.32 kN).[2]

Horsch and Patrick studied cadaver and dummy knee impact response at sub-fracture levels. Using rigid pendulum impacts of various masses ranging from 0.53 to 55 pounds (0.24 to 25 kg), knee impacts along the femoral axis of unembalmed male cadavers and Part 572 dummies were performed. The dummy was found to exhibit significantly higher knee

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[2]The authors felt that the localization of most of the fractures to the knee region was due to the use of a rigid impactor. Their analysis of the bending behavior of the femur during knee impact indicates that medial-lateral bending behavior of the femur was the dominant type of bending response, which is in general a beam-column behavior with bending in two planes as well as axial compression.

impact forces (1.5 to 3.7 times as great) than the cadaver subjects. This difference in response was shown to be due to differences of effective leg mass and knee padding (that is, soft tissue simulation), the dummy having a heavy rigid metal skeleton while the human has the major leg weight composed of loosely coupled flesh. The authors recommended that the "skeletal" weight of the Part 572 dummy leg should be substantially reduced (by a factor of approximately 10), with the weight difference being added to a properly simulated leg flesh, and that the knee flesh simulation be modified to reduce the peak force resulting from rigid body impacts.

Cooke and Nagel impacted the knee area of cadavers. Their conclusions were that the energy at impact and the peak force generated during impact are the parameters most significant in controlling trauma. Severity of trauma increases with increasing peak force and energy with 600 ft-lb. impact; no serious fractures were produced where the peak force was less than 1,700 pounds.

Cadaver patellas (knee caps) were subjected to various sized penetrators by Melvin et al. Depending on the diameter of the penetrator, the average failure load was 1,030 or 1,320 pounds with minimum failure loads at approximately half the average value.

Mather tested 44 pairs of unembalmed femurs. In static bending tests the mean energy required to fail specimens was 20-50 ft.-lbs., while impact loading velocity of 32 ft/sec. produced failure at 31-33 ft-lbs. Unfortunately these measurements cannot be directly related to maximum load without additional information.

Spears and Owen dynamically loaded cadaver femora, impacting them vertically. Neck fractures were found at 300 in-lbs. or less in poorly mineralized bones whereas mineralized specimens did not fracture until at least 600 in-lbs.

Roberts and Pathak conducted 36 dynamic torsion tests on cadaver femurs. They found an average torsional load carrying capacity of 154.7 Nm for males (118.3 Nm for females) at average loading rates of 26 KNm/ sec. and 18KNm/sec., respectively. All fractures were of the spiral type with an average energy input of 17.4 Nm.

Four unpublished studies have been conducted on the tolerance of
the leg. Snyder studied the crash loads on the backs of aircraft seats
caused by the legs of passengers striking the seat ahead. Using the FAA
bungee decelerator, four embalmed male cadaver legs were tested;
fracture of the tibia occurred at about 1,000 pounds peak load for each
leg. Young followed these preliminary tests with 12 more, using
embalmed cadaver legs on the FAA decelerator. In both of these studies
the mounted leg pivoted around the knee joint axis to swing forward
through approximately 60 degrees of arc to impact a steel bar during
impact. The site of impact was 3-6 inches above the ankle joint.
Maximum peak loads ranged from 1,050 to 2,000 pounds. It was noted that
the relatively low compression characteristics of tibial bone under
loading will offer high resistance until fracture occurs. The specimens
were from male cadavers 29-57 years of age.

Frank et al., also using the FAA decelerator, impacted freshly
amputated human legs. At 3000 lb. loads, fresh teenager legs were not
fractured.

An extensive unpublished study of lower leg impacts was conducted
by Mather, using 318 fresh cadaver legs subjected to different energy
levels delivered at a velocity of 13.84 ft/sec. A 9.2 pound weight was
dropped vertically, striking midway between the ankle and knee. Load
levels in fracture of the tibia in 5%, 50%, and 95% of the population
were calculated by probit analysis. The results were 25.4 ft-lbs., 55.3
ft-lbs., and 85.1 ft-lbs., respectively. The tibia of both females and
older persons required smaller loads to fracture than males or younger
individuals.

Kramer et al. frontally impacted the tibias of more than 200 human
cadavers. The lowest fracture level was at 2,200 lb. with an 8.5 inch
diameter cylinder. Carothers et al. tested five femurs in vertical
compression; fracture occurred through the femoral neck in four
specimens at an average of 1,990 pounds. The fifth bone fractured in
the shaft at 2,390 pounds.

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