Functional Anatomy of Vertebral Column with Reference to Load Bearing Areas

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Introduction

In aviation, human spine is exposed to high magnitude forces of varied profiles leading to different injury patterns. Changes due to ageing process and lack of methods to detect minor damage complicate the predictability of injuries. One has to fall back on functional anatomy and physiology to understand the mechanics of spinal injuries.

Vertebral Column

Anatomy of the human vertebral column is unique in many respects. Adoption of the upright stance has imposed mechanical stresses which are not found in other animals. The spine stripped of its musculature may be considered as a modified elastic pole in mechanical terms. It is the main axis of the body. In the anthropoid ape and man it forms vertical axis described as orthograde. The most primitive form of axial support is the notochord. In all vertebrate animals it is reinforced by a segmented vertebral axis. A spinal column is comprised of 33 bony elements (vertebrae), the lower most 9 vertebrae are fused to form 2 single bones namely sacrum and coccyx (Fig. 1).

Pyramids of Spine

The spine when viewed from the front appears to be made up of four Pyramids (Fig. 2). Comparative anatomical studies show this only in the human skeleton. The spinal pyramids are:

(*i*) Cervical
(*ii*) Upper Dorsal
(*iii*) Dorso Lumbar
(*iv*) Sacro Coccygeal.

Bases of cervical and upper dorsal meet at the disc between C7 and T1 and those of dorso lumbar and sacro coccygeal between L5 and S1.

Spinal Curves

Viewed laterally the normal adult spinal column has four prominent curves. Two primary and two secondary arranged in an alternating convex concave arrangement. Until the third month of foetal life, only one curve with anterior concavity is evident. At the beginning of fourth month, the sacro vertebral angle forms between the lumbar and sacral region. Soon after birth the cervical and sacral curves appear but the sacral is not to a pronounced extent. The lumber curve appears as the child learns to walk. It is produced to align the body vertically over the the lower extremities. The sacral and cervical curves also become more marked. The dorsal curvature, the flexible cervical bend and the sacro-vertebral angle are primary curves developed due to adoption of erect posture. The primary curves are due to shape of the vertebrae and the secondary due to shape of vertebral discs. Opinions are divided on which is physiologic – the slight lordotic curve of the cervical spine or the straight alignment. It has been claimed that a certain physiologic scoliosis of the vertebral column exists. In cervical and upper thoracic area and in lumbar area a curvature to the left in about 80% is present. A compensatory curvature exists in the lower thoracic region towards right. In the remaining 20% the conditions may be reversed[1].

Range of Movement

The total mobility of the spine in relation to the sagittal plane has been calculated by Bakke[1] at 219° and lateral mobility of about 70°–80°.

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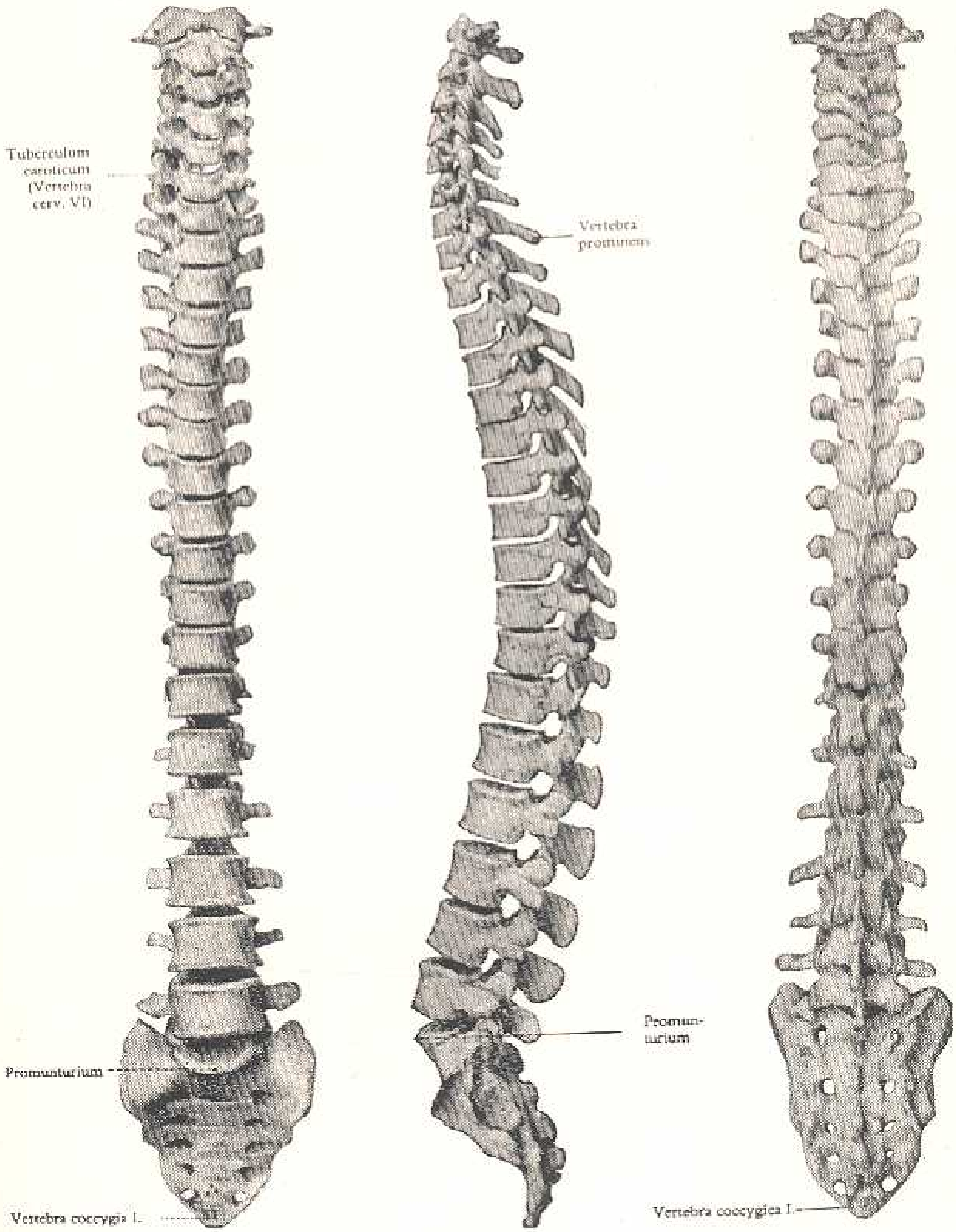


a ANTERIOR VIEW — b LATERAL VIEW — c POSTERIOR VIEW

Fig. 1
Skeleton of a human spine.

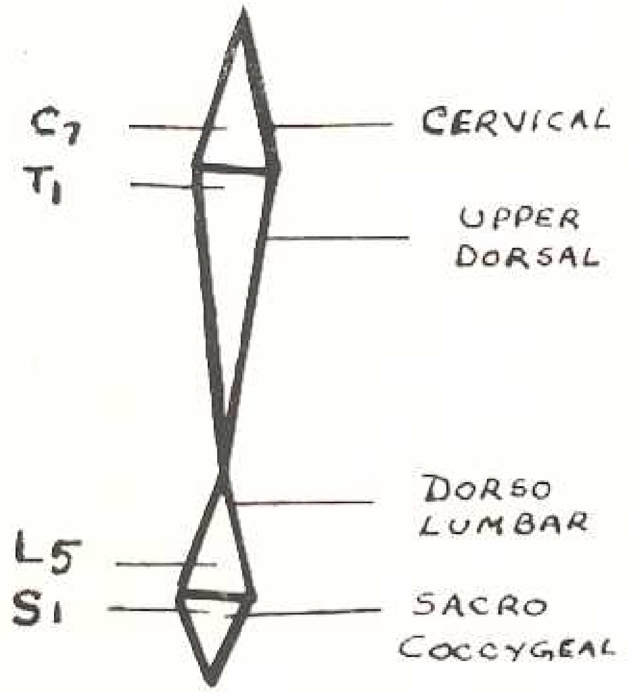


FIG 2 PYRAMIDS OF SPINE.

Detailed investigations on the oscillating mechanical behaviour of the spine has been reported by various workers (Fig. 3). Half the rotational mobility takes place between the atlas and the axis, and the other half in the area between C2 and C7. 50% of flexion and extension takes place in the skull articulation. The segments between C5 to C7 show least mobility.

Load Bearing and Weight Transmission

Significant contributions to experimental spinal biomechanics were made by Ruff[2], who was interested in the determination of the breaking strength of vertebrae under axial compression. Vertebral body force transmission during acceleration is dependent upon the body weight supported by that particular vertebra. Ruff[2] ascertained the percent of total body weight supported by the individual vertebral bodies. He found a relatively constant increase in percentage body weight supported by successive vertebrae from T8 to L5. Extrapolating upwards in a constant 3 percent decrease per vertebra, Stech[7] arrived at a calculated 9 percent value for T1. The head and neck has indeed been measured as being approximately 9% of body weight.

Table I presents Ruff[2] original T8–L5 data along with Stech's interpolated T1–T7 values.

Table I

Vertebra	Percent Body weight carried	Weight carried in Pounds of a 160 lb man	Breaking Strength in Pounds	Breaking Loan in G
T1	9	14.4	360	25
T2	12	19.2	480	25
T3	15	24.0	600	25
T4	18	28.8	720	25
T5	21	33.6	840	25
T6	25	40.0	1000	25
T7	29	46.4	1160	25
T8	33	52.8	1315	24.9
T9	37	59.2	1493	25.2
T10	40	64.0	1632	25.5
T11	44	70.0	1700	24.2
T12	47	75.2	1757	23.4
L1	50	80.0	1790	22.4
L2	53	84.8	1925	22.7
L3	56	89.6	2160	24.4
L4	58	92.8	2168	23.4
L5	60	96.0	2366	24.6

The weight of the upper half of the trunk is partly borne by and transmitted to the lower dorsal region by the sternum and ribs, which thus relieves the spine to some extent. At the sacrum the weight is transferred to the pelvis and lower limbs. A well marked thickening or bar in each ilium runs from the auricular surface to the accetabulum along the pelvic brim and transmits the weight to the femora.

Functional Anatomical Units

The two major functional anatomical units responsible for static, dynamic and kinetic functions of the spine are:

(*i*) Osseous Vertebral body with end plates.

(*ii*) The motor segments interposed between the vertebral bodies.

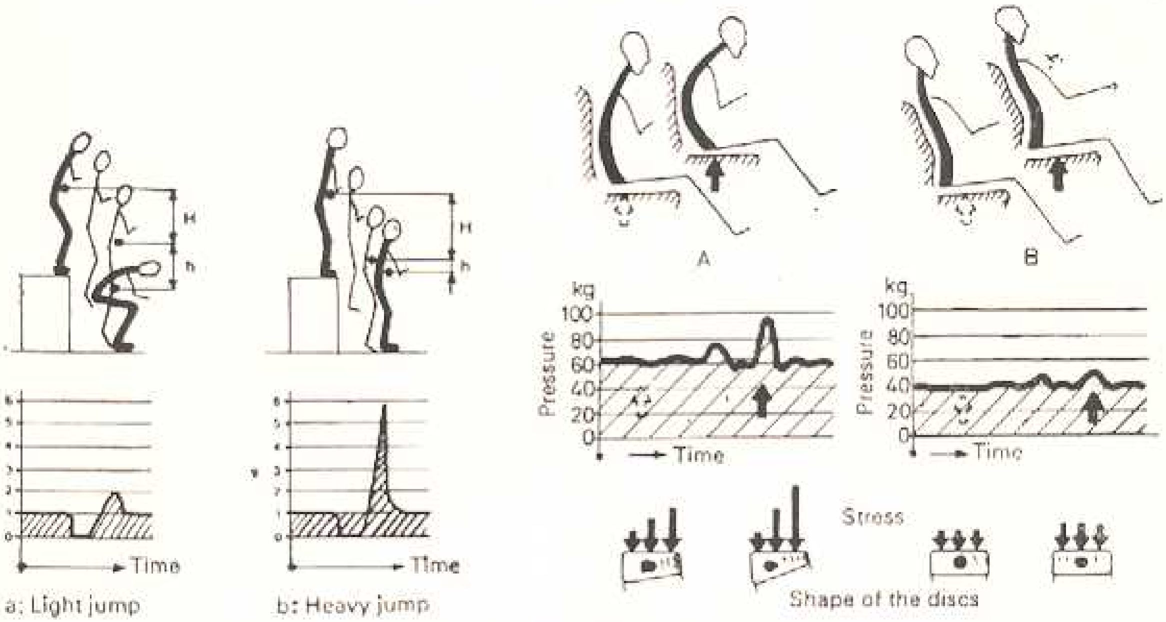


Fig. 5

(i) Stresses on the spine from soft and heavy jumping.

(ii) Stress on the lumbar spine and its discs from light blows in incorrect (A) and proper (B) sitting postures in an automobile.

OSSEOUS VERTEBRAL BODY WITH END PLATES

The osseous strength is determined by the structure of the trabeculae, firmness of the periphery and total volume. Morphology and architecture of a typical vertebra is shown in Fig. 4. The cervical vertebrae have a slender form, whereas the lumbar are much broader and have a considerably greater volume with their weight bearing surface plates being particularly broadly developed. Osseous tissue quickly readjusts to newly created conditions of stress. It is composed of mineral apatite, dispersed in protein collagen matrix. The former has high compressive strength and the latter low stiffness quality. Their combination yields a material which has high compressive tensile stiffness property. Experimental biomechanical studies of Ruff[2] have established the breaking strength and percentage of body weight supported by each vertebra. Compression fractures are a direct result of mechanical forces. The vertebral end plates located at the upper and lower surface of each vertebra are the key elements. Biomechanical investigations of Perry[2] showed that fractures of the anatomically distinct vertebral end plates occurred at levels lower than vertebral body proportional limit.

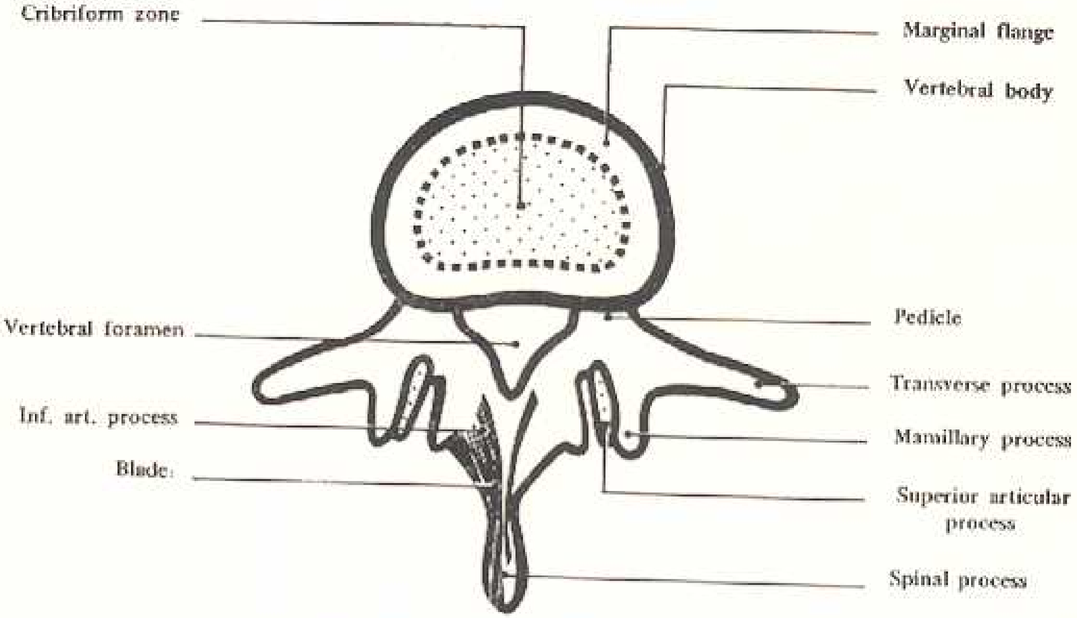
TABLE II

Distribution of Endplate Breaking Strength (Stech[2])

Vertebra	Mean Breaking Strength (Pounds)	Standard Deviation (Pounds)
L1	982	280
L2	1063	305
L3	1112	316
L4	1178	338
L5	1194	343

MOTOR SEGMENT

The segmental structure of the vertebral column with its co-ordinated motor spaces arranged between the bony vertebrae has been called as motor segment by Junghanns. As functioning parts of motor segments, we must consider the Amphiathrosis intervertebral disc (with annulus fibrosus, the



Thoracic or lumbar vertebra (after Paturet)

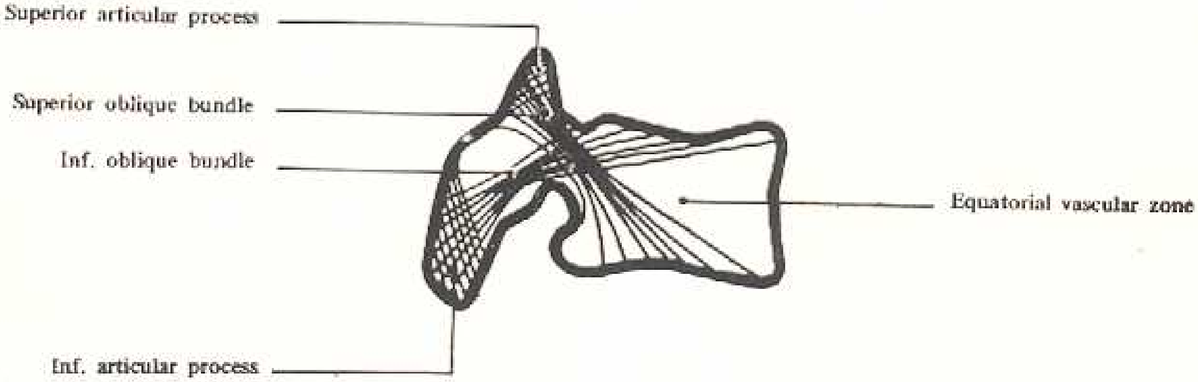


Fig. 4
Morphology and architecture of a vertebra (Note the cross-supports for the processes).

nucleus pulposus and the cartilagenous end plates), the anterior and posterior longitudinal ligaments, the appophysical joints and the ligamentum flava.

INTERVERTEBRAL DISC

The largest mass of the motor segment tissue is the intervertebral disc (Fig. 5). The fibrocartilagenous intervertebral disc positioned between successive vertebral bodies, constitute from 1/4 to 1/3 of total height of spinal column. The segmental arrangement of the mobile elastic disc tissue serves as an excellent shock absorbing device. The structural integrity is maintanied by the fibrous ring and strong inter locking between the disc tissue and the bony vertebrae. Each inter vertebral disc is made up of three distinct but anatomically combined parts.

ANNULUS FIBROSUS

The fibrous or lamellar ring forms the largest tissue part of the intervertebral disc. The ring consists of screw like extending lamellae composed of cartilagenous fibres positioned closely to each other with their directions being at angles to each other. Anteriorly the fibrous ring is broad and the individual lamellar strands are well developed

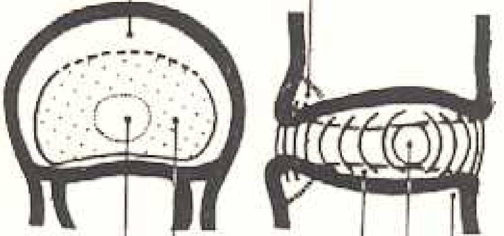


Fig. 5
Architecture of an Intervertebral disc.

where as posteriorly only a small zone of the fibrous ring is present in which the individual lamellae are more delicate. This may be seen in horizontal as well as sagittal cuts. Fick[2] has described the delicate structures in detail and Schmorl[1] demonstrated the existence of "spanning fibres." In the area of the bony rim where the cartilagenous plate is missing the fibres extend as Sharpe's fibres. In this way a particularly firm connection takes place between the bony rim and the annulus fibrosus. Brown[2] after testing older specimens, documented unsymmetrical bulge during compression. The bulge was noticed in the strongest anterior portion. If the hydrostatic pressure was solely responsible, logically the bulge should occur in the weaker areas of the annulus. Asymmetrical loading due to bending, causing direct compression appears to be the cause for bulging to occur in the strongest portion. The annulae are capable of support and energy dissipation as supported by clinical evidence.

NUCLEUS PULPOSUS

The nucleus pulposus originates in the intervertebral chorda which remains in the disc space and is filled with mucoid like ground substance. The nucleus pulposus is the weight absorbing and distributing central point of the disc, a functional source of vertebral strength. The hydrophylic muco-polypeptides in the nucleus pulposus have great capacity to absorb water. The pressure experiments of Hirsch and Nachemson,[1] have yielded interesting results on the resistance of disc tissue. Impulse loading causes oscillations of the disc. Intervertebral disc is a dynamic system, with the mass of the disc in constant motion. There is however, a lack of study on the mechanical ability of the intervertebral disc tissue to resist pressure, torsion and displacement upto the point of disruption. Further it remains to be clarified where the first tear takes place if the threshold of resistance is exceeded.

The chemical aspects of vertebral disc have been investigated to a great depth. The two principal macro-molecules of the disc namely collagen and protein polysaccharide are synthesized intracellularly. Hydroxylation of collagen, the mechanism of linkage between protein and polysaccharide and sulphation of polysaccharide are yet not clearly understood. Significant chemical events take place extracellularly. One of the unique features of the disc and more particularly its nucleus is the presence of more than one kind of polysaccharide on a single protein core. The biologic importance of protein-polysaccharide and collagen is their formation of a particular matrix to serve the mechanical and chemical functions of the disc. The muco-polysaccharide content decreases with advancing age. The chondroitin 4 sulphate is displaced in favour of chondroitin 6 sulphate. Nutrition to the disc is by a process of perfusion from neighbouring tissues. The nerve supply is not fully understood.

Other important parts of the motor segment are the ligamentous connections, extending between the adjacent vertebral bodies. These include anterior and posterior longitudinal ligaments, the ligaments between the vertebral arch processes, spinous processes and ligamentum flava. The spinal muscles bridge, limit and co-ordinate the range of motion.

The motor segments are important for the shape and mobility of spine. The weight of the head and the arms, the weight bearing capacity of the pelvis and lower extremities have significant influence upon the functions of the spine. Tightening of the abdominal muscles converts the cavity into a piston lying anterior to the spine. As much as 50 percent reduction of force on the spine has been calculated to result from the piston effect. The mobility of the spine is not only influenced by the inter vertebral disc but also by the appophyseal joints. The position of these joints show substantial difference in various spinal segments. Although the mobility of each joint pair is not great, the total mobility of several adjacent articulating pairs permits considerable range of movement.

The following functional anatomical aspects of human spine are of fundamental importance in aviation.

(*i*) End plate fractures occur at load levels significantly below those required to produce compressive vertebral body fractures. This appears to be true about damage to other soft tissues.

(*ii*) Because of restricted mobility of C5-C7 in whip lash injuries this segment is highly vulnerable.

(*iii*) The thoraco lumbar junction, an important transitional zone because of various anatominal considerations, already explained, carries high injury potential.

RECOMMENDATIONS

(*i*) To reduce incidence of spinal injuries in aviation there is need for re-evaluation of physiologically acceptable limitations of forces, currently accepted in aircraft and escape system design.

(*ii*) Further studies are required to evolve techniques to discern minimal damage to spine caused in aviation.

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