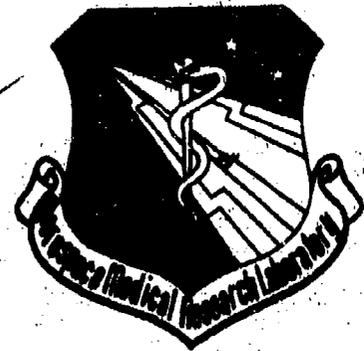


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FLIGHT PHYSICAL STANDARDS OF THE 1980'S: SPINAL COLUMN CONSIDERATIONS

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FOR THE COMMANDER



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Director
Biodynamics and Bioengineering Division
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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The introduction of a new generation of high performance fighter (HPF) aircraft (F-15, F-16, A-10) into the inventory makes it essential that physical standards used for both the selection and continued qualification of pilots for these systems be carefully reviewed. It is felt that HPF selectees should require additional radiological examinations to insure they do not have architectural anomalies of the spinal column that could be aggravated by or potentially result in pilot incapacitation while flying or during emergency escape. This paper provides a critical biomechanical analysis of the role of selected preexisting | | |

congenital anomalies or diseases as a source of decreased spinal tolerance. The following congenital or developmental defects are discussed: scoliosis, spondylolysis, spondylolisthesis, Klippel-Feil syndrome, Scheuermann's disease and spondylosis deformans. In addition, the role of vertebral body fractures on subsequent spinal column impact is discussed.

PREFACE

The research reported in this paper was performed at the Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, under project 7231-11-01. Colonel Belk is Chief of the Life Sciences Division, Air Force Inspection and Safety Center, Norton Air Force Base, California.

A symposium held at Brooks Air Force Base, 3-5 April 1979, was entitled "Flight Physical Standards of the 1980's." The objectives of this symposium were to resolve and clarify problems and issues related to pilot selection and to develop physical standards for the selection and continued qualification of pilots in a dual track system.

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I. INTRODUCTION

Spinal column disorders affect a significant segment of the flying population and are at one time or another a major cause of pain, weakness, and impaired endurance. Although much has been written about the frequency, severity, and mode of operational spinal column injuries, little is documented about the incidence of back pain, severity of injury, or probability of risk of aircrewmembers *without* congenital or acquired structural defects versus those aircrewmembers *with* preexisting spinal column defects.

The tactical aircraft being introduced into operational service by the Air Force include the F-15 and F-16. These high thrust-to-weight ratio aircraft with unmatched capabilities for maneuverability, acceleration, and speed have substantially expanded the flight envelope. Technological developments now in their embryonic stages will continue to change the patterns of weapon systems development radically; and significant performance gains in terms of nonconventional flight modes, e.g., flat turns, vertical or lateral translation, will enhance the operational capabilities of the future generation of high performance fighters. These technological developments have altered the force-time histories normally experienced by an aircrewman throughout the flight envelope. The combined mechanical stresses experienced on an aircrewman have become increasingly acute; are far greater than previously experienced; and are potentially capable of interfering with an aircrewman's safety, health and operating efficiency. Maximum limits are no longer dictated by structural constraints or by handling limitations of the aircraft, but rather by the physiological and musculoskeletal (e.g., bone strength) tolerance of the aircrewman.

In this report, we will attempt to answer the questions: What spinal conditions/defects should be disqualifying for high performance flying? Under what conditions would you consider a waiver for these conditions and defects?

A moot question remains as to how great a role anomalies of the spinal column play in causing back symptoms. The clinical literature is not particularly revealing. Statistics and opinions can be found supporting or refuting the role congenital or developmental anomalies play with respect to symptomatology, or spinal instability. In any event, we believe that the anomalies listed in this investigation are important not only as a causative factor in the production of symptoms, but also may be the basis for decreased biomechanical strength and alleged disability when revealed radiologically after injury.

The opinions expressed in this paper result from roentgenographic analyses of normal and postejction radiographs, long-term follow-up investigations of ejected aircrewmembers, and biomechanical studies conducted on spinal column elements excised from normal and pathologic cadaveric material and subhuman primates. The objectives of these efforts are to shed additional light on the mechanism of injury in relation to functional anatomy to understand the variations in strength following exposure to mechanical stresses.

Certain spinal column anomalies found by X-ray appear to represent an inherent mechanical weakness of spinal column architecture, that is capable of becoming activated by back strain, and precipitating or aggravating underlying lesions which previously had been quiescent and did not produce sufficient symptoms to cause the aircrewman any concern. Such being the premise, if an aircrewman with known postural defects or congenital anomalies of development, or both, is subjected to unaccustomed muscular activity, abrupt accelerative forces, buffeting, and high G, the acute and long-term episode of trauma that may ensue may have a profound influence on the delicate relationship between the deformed bony element, adjacent intervertebral disk, and neurologic structures resulting in minor and major degrees of trauma greater than normally expected.

Air Force Regulation 160-43, "Medical Examinations and Medical Standards" establishes entry medical standards for flying personnel. Paragraph 4-29, Spine and Other Muscle Skeletal, lists a number of spinal column disorders that may be causes for aircrew rejection. For purposes of reference, 4-29 is reproduced below:

"4-29. Spine and Other Muscle Skeletal. Causes for Rejection: Enlistment, Commission, and Flying, Classes I, Ia, II, and III:

- a. History of disease or injury of the spine or sacroiliac joints, either with or without objective signs, which has prevented the examinee from successfully following a physically active vocation.
- b. Arthritis of the spine, all types.
- c. Granulomatous disease of the spine, active or healed.
- d. Scoliosis of more than 20 degrees as measured by the Cobb method.
- e. Abnormal curvature of the spine of any degree in which there is a noticeable deformity when the examinee is dressed, in which pain or interference with function is present, or which is progressive.
- f. Spondylolisthesis; spondylolysis, if symptomatic.
- g. Herniated nucleus pulposus, or history of surgery for that condition.
- h. Healed fractures or dislocation of the vertebrae. A compression fracture involving less than 25 percent of a single vertebra is not disqualifying if the injury occurred more than a year before examination and the examinee is asymptomatic. History of fractures of the transverse processes is not disqualifying if the examinee is asymptomatic.
- i. Spina bifida when more than one vertebrae is involved, or if there is dimpling of the overlying skin.
- j. Juvenile epiphysitis with any degrees of residual change by X-ray kyphosis.
- k. Fixed elevation and rotation of the scapula (Spengel deformity) which materially interferes with shoulder girdle function.
- l. Torticollis, congenital or spastic, which interferes with normal neck function.
- m. Cervical rib with demonstrable neurologic or circulatory deficit.
- n. Osteomyelitis of a rib, sternum, clavicle, scapula, or vertebrae.
- o. Deficient muscular development."

We propose to modify and/or expand the current number of spinal column disorders that may be causes for aircrew rejection. The following is a listing of spinal column defects considered to be of actual or potential significance with respect to human spinal tolerance. The following acquired or congenital spinal column defects are thought to increase susceptibility to spinal column trauma, and, if trauma does occur, the effects might be especially severe both in the short- and long-term consequences. This listing identifies disorders encountered in aircrewmembers currently flying ejection seat aircraft who are currently experiencing back pain thought to be due to aggravation of a preexisting condition causing few, if any, symptoms until the individual was subjected to greater or unusual stresses while flying.

II. Congenital and Developmental Defects

Scoliosis
Spondylolysis, Spondylolisthesis
Klippel-Feil Syndrome
Scheuermann's Disease
Spondylosis Deformans

III. Vertebral Body Fractures

II. CONGENITAL AND DEVELOPMENTAL DEFECTS

SCOLIOSIS

Scoliosis is defined as an abnormal lateral structural curvature of the spinal column that possesses a lack of normal thoracic spine flexibility. The ultimate effect is an extensive alteration in the structure and response of the spine to static and dynamic loads. The etiologic factors in scoliosis involve:

- heredity
- pathological conditions of the vertebrae
- congenital anomalies
- epiphyseal changes
- muscular imbalance
- inequality in length of legs and other structures

There are two primary types of scoliosis: postural and structural. A postural scoliosis is described as a curve that disappears on suspension or during recumbency. The curve is unilateral, unaccompanied by structural changes in the vertebrae. With structural scoliosis, vertebral body rotation is present, and there are definite geometric changes in the individual vertebral bodies and intervertebral disks. (Harrington, 1964; Moe, 1973; Roaf, 1977)

Currently, AFR 160-43 identifies a scoliosis, measured by the Cobb technique, of up to twenty degrees to be acceptable for flying personnel (Just how this number was realized remains uncertain). Beyond 20° the view is expressed that the intended function of the vertebral column structure as a whole is altered. The efficiency of the inherent mechanics is gradually lost, and forces are so transmitted that something other than bony reaction is required to prevent progression.

We recommend that if an individual has had any prior surgical interventions, spinal instrumentation (e.g., Harrington rods), and/or fusion to correct a spinal (to bring the deformity within the 20° limit) deformity, that individual should not be considered under any circumstances as a candidate for flying high performance aircraft.

SPONDYLOLYSIS AND SPONDYLOLISTHESIS

• *Spondylolysis*

Although spondylolysis and spondylolisthesis are linked as a related condition, no one is certain that they are etiologically the same.

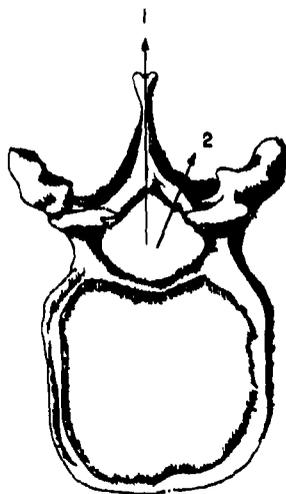
One of the principal functions of the neural arch is to stabilize the spine. At the lumbosacral level, the 5th lumbar vertebra supports the superimposed weight of the torso upon the inclined plane of the sacrum. The necessity for bony continuity of the 5th and inferior articular processes with the superior articular processes of the sacrum is obvious.

The malformation most commonly encountered in the vertebral arches is a cleft. The various clefts encountered are illustrated in Figure 1 and are identified as:

- (1) cleft in the pars interarticularis (spondylolysis, spondylolisthesis).
- (2) sagittal cleft of the spinous process (Spina Bifida Occulta).

Spondylolysis refers to a mechanical failure in the pars interarticularis without any relative vertebral body slippage. Spondylolysis is probably due to congenital failure of union between the normal anterior and posterior centers of ossification of the vertebral arch. The failure of union takes place just at the base of the lateral articular facet. Spondylolysis is most commonly found in the fifth and less so in the fourth lumbar segments (Meschan, 1973; Weinstein, 1977). Clinical evidence suggests that an individual with a pars defect will have a 25% greater likelihood of back disorder than an individual without the defect. A pars defect also is likely to increase the rate of intervertebral disk degeneration. Intervertebral disk degeneration is accentuated by loss of posterior vertebral column stability. Mechanical forces and particularly torsional stresses seem to be most detrimental and increase the onset of disk degeneration.

MALFORMATIONS OF THE VERTEBRAL ARCH



1. SAGITTAL CLEFT SPINOUS PROCESS (SPINA BIFIDA)
2. CLEFT IN PARS INTERARTICULARIS (SPONDYLOLYSIS, SPONDYLOLISTHESIS)

FIGURE 1 — Illustration of the various clefts encountered in the vertebral body (redrawn from Schmorl G. and Junghanns H., *The Human Spine in Health and Disease*, Grune and Stratton, New York, 1959).

We suggest that aircrewmembers with spondylolysis, asymptomatic or not, be a cause for rejection from high performance flying. No waivers should be granted.

- *Spondylolisthesis*

Spondylolisthesis refers to a defect in the pars interarticularis with forward migration on a subadjacent vertebra, usually the fifth lumbar on the sacrum (Adkins, 1955; Wiltse, 1962).

Whether spondylolysis is the cause of spondylolisthesis remains a subject of controversy. Scientific evidence does not support the theory that under mechanical loading the bridged fibrous tissue can stretch or give way leading to separation of the vertebral arch (spondylolisthesis) into an anterior superior part (consisting of the centrum superior articular process and transverse process) and into an inferior posterior part (consisting of the inferior articular process and the posterior part of the arch including the spinous process). The issue centers around whether a defect in the pars interarticularis is the result of developmental changes (progression of the slipping process) or if it is an acquired cleft formation.

The etiology of spondylolisthesis is unknown. The incidence in the Air Force is unknown. Delehay and colleagues (1970) have reported an incidence of 2.3% in French aircrewmembers.

In the normal spinal column, forward displacement of a vertebral body is prevented by the engagement of the articular processes with those below it. In spondylolisthesis, there is a failure of this natural accommodating check mechanism. The attachments of the longitudinal ligaments and intervertebral disk alone do not possess adequate strength to prevent forward slipping, and, as a consequence, vertebral column alignment is compromised.

There are no proven demonstrations in which the aggravation of the defect has been shown in the course of time. Limited operational evidence exists pointing to the fact that high G maneuvering may aggravate the defect resulting in acute back pain. Figure 2 shows a typical Grade I spondylolisthesis. Figure 3 illustrates spondylolisthesis at the L4-L5 level accompanied by intervertebral disk degeneration at the L4-L5 and L5-S1 levels.

In summary, any cleft in the pars interarticularis results in an area of decreased resistance with regard to weight bearing, load transmission, and load attenuation. Aircraft maneuvers may place undue stresses involving the lumbosacral transition leading to severe back pain and the increased probability of trauma. It is suggested that spondylolisthesis, asymptomatic or not, be cause for rejection by aircrew for flying high performance aircraft. No waivers should be granted.

KLIPPEL-FEIL SYNDROME

The Klippel-Feil syndrome is associated with extensive fusion and deformed cervical vertebrae giving rise to hemivertebrae and irregularities in the laminae and spinous processes and results in restricted neck motion and, frequently, neurological phenomena depending on the degree of pathology.

Typically, several vertebrae (two or more) are joined in various degrees of partial fusion, either via continuous spinous processes or the respective vertebral centra, or often separated by a vestigial disk. The posterior articulating processes are nonexistent. The loss in the number of intervertebral disks and the decrease in the number of actual vertebrae may result in some spinal column shortening (Avery, 1936; Hensinger, 1975; Archives Pathology, 1946).

The deformity has been shown on routine examinations following severe complaint of neck pain at the onset of high-G maneuvering.

The deformity and the rigidity of the cervical spine make it susceptible to fracture from insignificant mechanical force input. The true etiologic factors of Klippel-Feil are unknown.

We suggest that aircrewmembers who have Klippel-Feil deformity be rejected from flying high performance aircraft. No waivers should be granted.



FIGURE 2 — Typical Grade I spondylolisthesis — a wide defect in the pars interarticularis of the fifth lumbar vertebra.



FIGURE 3 — Illustration of spondylolisthesis at the L₄-L₅ level accompanied by intervertebral disk degeneration at the L₄-L₅ and L₅-S₁ levels.

SCHEUERMANN'S DISEASE

Scheuermann's disease is defined as a rigid kyphotic deformity involving the lower thoracic spinal column. A lateral X-ray (Fig. 4) features (1) increased dorsal curvature, (2) anterior wedging of the vertebral bodies in the lower dorsal region, (3) blurring, irregularity and mottling in the cartilaginous end plate of the intervertebral disk and in the apophyseal ring of the vertebral body especially anteriorly, (4) herniation of nuclear material into the vertebral bodies. Strain, trauma or weakened areas, which exist as the result of involuted nutrient vessels, may allow prolapse of nuclear material through fissures or interstices in the cartilaginous end plate and become more apparent with time as a reactive ring of sclerotic bone forms about the protrusions. The protrusion of intervertebral disk material results in narrowing of intervertebral disk space. The practical importance of calling attention to narrowing of intervertebral disk space is usually regarded as indicative of a possible associated intraspongy disk herniation or degeneration. Disk degeneration usually in the long term is associated with osteoarthritis of the involved vertebra or adjacent vertebrae. The increase in thoracic kyphosis leads to a development of compensatory increase of cervical and lumbar lordosis to maintain the center of weight bearing. The kyphosis persists and secondary degenerative changes develop in the parts of the spine involved.

There are several theories of the pathogenesis of adolescent kyphosis (Schmorl, 1971). The actual etiology is unknown.

Figure 4 is a lateral radiograph of the thoracic spinal column of an aircrewman with Scheuermann's disease.

The intervertebral disks are involved with load transmission, load attenuation and spinal column mobility. Kyphosis establishes a weakened structure that may become unstable under dynamic loading.

The Schmorl's nodule is due to a protrusion of nuclear material into the spongiosa of the adjoining vertebra and results in a decrease in the volume of the disk, a loss in intervertebral disk elasticity (initially manifested by hypermobility) and, ultimately, a decrease in spinal mobility. Following prolapse of disk tissue into the adjacent cancellous bone, the architecture of the spongiosa is destroyed. The monotonous continuity of spinal loading widens the fissures and increases cartilaginous plate bulging. The disk undergoes a retrogressive change, and blood vessels and connective tissue penetrate through the fragmented cartilaginous end plates invading the disk, resulting in hemorrhaging into the nuclear cavity, extensive fibrotic changes and, ultimately, fusion of adjacent vertebrae (Schmorl, 1959). Increased loading on the anterior portion of the vertebral bodies produces vertebral body wedging, decreasing the efficiency of the vertebral body complex to attenuate and transmit dynamic load. Figure 5 shows typical Schmorl's nodes.

The incidence of Scheuermann's disease among USAF aircrewmen is unknown. It is suggested that aircrewmen who have Scheuermann's disease be rejected from flying in high performance aircraft. No waivers should be granted.

SPONDYLOSIS DEFORMANS

Pathologic disorder of the vertebral column is characterized by bony protuberances developing at the upper or lower marginal ridges of the vertebral bodies as a consequence of taking their departure in the intervertebral disks. The osteophytes tend to grow toward each other, gradually compressing the intervertebral disk and sometimes fusing the adjacent bony ledges. Regressive pathologic changes occur in an intervertebral disk. Opinions on the development of spondylosis deformans cannot be immediately correlated with clinical or experimental findings. The symptoms are usually asymptomatic.

Localized anatomical changes which may be radiographically visualized are advanced intervertebral degeneration, narrowing of the intervertebral foramen by a shift in the alignment of two adjacent vertebrae, and narrowing of the space between the articulating surfaces of the facets. If strain is imposed on a spinal column in which the intervertebral disks are already compressed by the action of the loading force, excessive strain upon or direct force to a spinal column initially produces fractures of the osteophytes at lower than expected mechanical loads.

The incidence of spondylosis deformans among USAF aircrewmen is uncertain. It is suggested that aircrewmen who have spondylosis deformans be rejected from flying high performance aircraft.



FIGURE 4— Scheuermann's Disease. Lateral projection shows increased thoracic curvature, wedging of vertebral bodies, herniation of nuclear substance with reactive changes in the vertebral bodies and decreased intervertebral disk space.

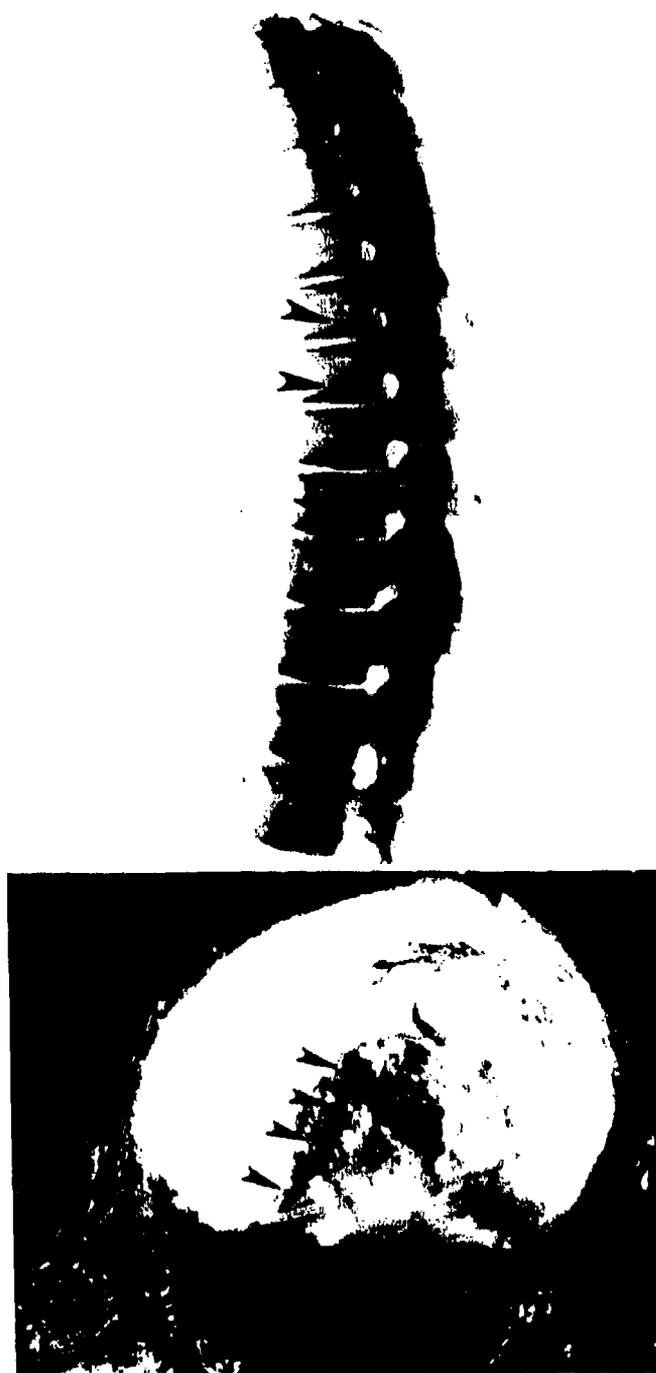


FIGURE 5 — *Top* — Typical Schmorl's nodes (arrows) radiographically visualized in an excised human spinal column.
Bottom — Coronal slice through the intervertebral disk revealing disruption in the cartilaginous end plate (arrows); note loss of nuclear material.

III. VERTEBRAL BODY FRACTURES

The spinal column is an articulated flexible structure whose geometry varies with every movement of the body. It supports the head and maintains the body in an erect posture. The human spine may be divided into an anterior and posterior column, for mechanically the role of these individual parts is markedly different. The anterior spinal column is made up of the vertebral centra, the intervertebral disks and the anterior and posterior longitudinal ligaments; the posterior spinal column consists of the articular facet joints along with their ligamentous structures. The anterior spinal column is responsible for load transmission and load attenuation. The posterior spinal column reacts as a stabilizer for the vertebral bodies and under certain conditions becomes a load bearing element. Fractures of the spinal column result from either directly or indirectly applied mechanical forces. Most operational injuries are the result of indirect mechanical forces in which one experiences hyperflexion, hyperextension, or shortening of the longitudinal axis of the column beyond its limit of elasticity. Examples of directly applied mechanical forces are seen under conditions of sudden lengthening of the longitudinal axis of the spinal column beyond the elastic strength of the ligaments, i.e., occipital/C₁ (C₁/C₂) separation.

Most operational fractures of the vertebral body are of the anterior wedge type not complicated by neurological damage. The distribution of trauma is greater in the thoracic and lumbar spine when compared to the cervical spine. Peaks of injury localization occur most frequently in T₄-T₇ and T₁₁-L₁. However, there is a wide scatter in distribution, and fractures have been seen at all levels from T₁ to L₅. The mechanism of injury is usually sudden hyperflexural motion. Compression fractures usually occur singly, but may involve adjacent vertebrae or be widely separated in the spine. Vertebral body compression produces the characteristic deformity shown in Figure 6. Typically, only the superior half of the vertebral body is affected. The fracture line extends from the superior posterior angle of the vertebral body to a point in the anterior surface. Note a line of increased density resulting from impacted fragments.

An anterior wedge compression fracture is the most common injury mode and produces roentgenographic features recognized by alterations in the shape or size of the vertebra, fragment displacement, solutions of continuity, and later, the development of callus. In the greater majority of operational injuries the geometry of the posterior and inferior two-thirds of the centrum usually remains intact. In vertebral centrum deformity, development of a radiographically exuberant callus in two to six weeks following trauma confirms the diagnosis of fracture that was previously doubtful or indicates the site of fracture was previously invisible on radiographic film.

Judgment of strength of the union at a fracture site is an extremely difficult matter to resolve. Of the radiologically visible factors, the most reliable may be an increasing density of callus, decreasing sharpness of definition of the surfaces of the fragments along with an increase in the density in the spaces between the fragments. Even when these changes have progressed to a marked degree, the strength of the union cannot be certain. An additional difficulty arises in the matter of the callus occupying the space which is subject to weight bearing. Callus is rarely sufficiently strong to hold up to weight bearing, impact or vibrational forces, and, therefore, there will always result an increase in the deformity with time until the callus is sufficiently knitted and toughened to mechanical stresses. The incidence of persistent symptoms and residual disability in ejected aircrewmembers is unknown. No supportive evidence has been found to link vertebral body compression and/or fusion in aircrewmembers to decreased spinal impact tolerance. A case in point is shown in Figure 7. This aircrewman sustained a compression fracture of L₅. He ejected and as a result, acquired the anterior wedge fracture at the L₁ level.



FIGURE 6 — Typical Grade III anterior wedge compression fracture due to hyperflexural forces following initiation of the escape sequence.



FIGURE 7— This aircrewman sustained an anterior wedge compression fracture at the L₅ level in an automobile crash. Six years later he ejected from an F-4 which resulted in the typical Grade I anterior wedge fracture with no further compression of L₅.

IV. CONCLUSION

Current Class I Flying Physical Standards (AFR 160-43) are inadequate for the musculoskeletal system with respect to high performance flying. The new high performance aircraft entering the inventory (A-10, F-15, F-16) have been specifically designed to provide the aircrewman with an advantage in performance capability. These systems are capable of rapid onset and high sustained "G" which can easily exceed a pilots physical and physiological limitations. It is felt that certain spinal column anomalies found by x-ray represent an inherent mechanical weakness of spinal column architecture that is capable of becoming activated by back strain and precipitating or aggravating underlying lesions which previously had been quiescent and did not produce sufficient symptoms to cause the pilot any concern.

The spinal abnormalities considered in this paper include: scoliosis, spondylolysis, spondylolisthesis, Klippel-Feil syndrome, Scheuermann's disease, spondylolysis deformans and vertebral body fractures.

It is our opinion that systematic standardized radiographic skeletal investigations should be conducted on all aircrewmen recommended for high performance flying. If congenital or acquired anomalies are found the radiographs should be used as an adjunct for consideration for high performance flying.

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