Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Aerospace Medical Research Laboratory Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

VARIATIONS OF SPINAL ALIGNMENT IN EGRESS SYSTEMS AND THEIR EFFECT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

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6. REPORT DATE September 1969	7a. TOTAL NO. OF PAGES 6	7b. NO. OF REFS 6

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) AMRL-TR-67-232
b. PROJECT NO. 7231	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES Reprinted from Aerospace Medicine, Vol. 40, No. 9, September 1969.	12. SPONSORING MILITARY ACTIVITY Aerospace Medical Research Laboratory, Aerospace Medical Div., Air Force Systems Command, Wright-Patterson AFB, OH 45433

13. ABSTRACT

Fractures of the vertebral column constitute a serious and undesirably common medical complication of otherwise successful ejections from high performance aircraft. The reported incidence of spinal compression fractures attributable to the ejection forces exhibits a more than tenfold variation when the specific fracture rates associated with the several aircraft-ejection-seat systems currently used by the United States and Allied Armed Forces are compared. A variety of seat design factors have been suggested as having primary causal importance to explain the observed difference in injury rates. A study was therefore conducted to investigate quantitatively the influence of seat geometry and personal equipment design factors on the intrinsic spinal curvature and vector relationship with the catapult thrust axis. Fourteen male Air Force volunteers, encompassing the 5-95 percentile range of sitting heights, were x-rayed while seated with an ejection posture in the F/RF-4C and F-105 ejection seat systems. Quantitative roentgenometric techniques were used to accurately determine individual vertebral body locations and measure absolute differences governed by seat design features. The sizable differences observed are discussed in terms of biodynamic injury mechanisms, and recommendations for improved seat design are derived.

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Variations of Spinal Alignment in Egress Systems and Their Effect

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Mohr, G. C., J. W. Brinkley, L. E. Kazarian and W. W. Millard. *Variations of spinal alignment in egress systems and their effect.* Aerospace Med. 40(9):983-988. 1969.

Fractures of the vertebral column constitute a serious and undesirably common medical complication of otherwise successful ejections from high performance aircraft. The reported incidence of spinal compression fractures attributable to the ejection forces exhibits a more than tenfold variation when the specific fracture rates associated with the several aircraft-ejection-seat systems currently used by the United States and Allied Armed Forces are compared. A variety of seat design factors have been suggested as having primary causal importance to explain the observed difference in injury rates. A study was therefore conducted to investigate quantitatively the influence of seat geometry and personal equipment design factors on the intrinsic spinal curvature and vector relationship with the catapult thrust axis. Fourteen male Air Force volunteers, encompassing the 5-95 percentile range of sitting heights, were x-rayed while seated with an ejection posture in the F/RF-4C and F-105 ejection seat systems. Quantitative roentgenometric techniques were used to accurately determine individual vertebral body locations and measure absolute differences governed by seat design features. The sizable differences observed are discussed in terms of biodynamic injury mechanisms, and recommendations for improved seat design are derived.

SPINAL COMPRESSION fracture continues to be one of the most common of the major injuries associated with otherwise successful ejection from disabled high performance aircraft. The possible causal relationships are readily divided into the classical triad of "host" factors such as the crewman's age, anthropometric characteristics, or preexisting skeletal abnormalities; "agent" factors, such as acceleration magnitude, velocity change, and pulse shape; and "environmental" factors, such as seat geometry, mode of restraint, and type of comfort materials. An extensive literature has accumulated both from the analysis of accident data and from laboratory experiments providing considerable insight into these causal relationships. Specifically, the influence of egress system design and restraint system design on preejection posture has been shown to be an important factor modifying the crewman's tolerance to imposed accelerations. Chubb, et al,[1] performed a statistical analysis of 928 United States Air Force ejections occurring during 1960 through 1964 and concluded that for the ejection seats then in the inventory, the preservation of an erect ejection posture was the most significant contributing factor in the prevention of compression fractures. Levy[2] has previously incriminated poor body position resulting from improper seat and restraint system design as a major factor in the genesis of spinal compression fracture. He emphasized that any extension or flexion of the spine changing the "normal" thoraco-lumbar curvature produces abnormal stress concentration on the vertebral bodies, decreases the energy absorbing capacity of the intervertebral discs, and promotes the occurrence of compression fracture during ejection. Brinkley[3] has compiled a summary of egress system catapult performance characteristics. These data indicate generally that catapults in current use impart accelerations of sufficient magnitude to account for the observed ejection fracture rates, except for one notable exception. The Air Force noncombat experience with the RF/F-4C egress system during the period[4] 1 January 1964 through 20 October 1966 indicated an ejection fracture rate of nearly 40 per cent. This fact together with the known misalignment of the crewman's backline with the catapult thrust line[5] prompted a comparative analysis of body position and intrinsic spinal curvature as a function of seat and restraint system geometry. The roentgenometric technique used by previous investigators was modified to maximize the quantitative accuracy.[6] This report presents data defining the changes in spinal curvature and included angle (spinal alignment with the catapult thrust axis) attributable to selected hardware design features of the RF/F-4C egress system compared to a standard Air Force seat geometry. The significance of poor preejection posture is discussed.

METHODS

Since the possible number of seat-man interactions that could conceivably influence body position is almost

The research reported in this paper was conducted by personnel of the Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. This paper has been identified by Aerospace Medical Research Laboratory as AMRL-TR-67-232. Further reproduction is authorized to satisfy needs of the U.S. Government. The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-8.

TABLE I. VARIABLES UNDER STUDY

INDEPENDENT VARIABLES	DEPENDENT VARIABLES
1. Seat Design Factors	1. Spinal Curvature
a. RF/F-4C Seat	a. Flexion
b. F-105 Seat	b. Extension
2. Equipment Design Factors	2. Included Angle
a. Back Pad	3. Pelvic Angle
(1) Flat	
(2) Contoured	
b. Seat Belt/Seat Cushion	
3. Subject Sitting Height	

Fig. 1. Subject P.T. F-105 configuration.

Fig. 2. Subject P.T. RF/F-4C configuration.

infinite, the selection of independent and dependent variables for the study was made somewhat arbitrarily on the basis of the priority needs of the Air Force at the time the investigation was planned. The independent and dependent variables chosen are listed in Table I. To provide operational authenticity, actual Air Force ejection seats were used together with standard restraint harness, comfort materials, and personal equipment. The RF/F-4C seat refers to the H-5 model being used in Air Force operations at the time that this study was accomplished (1966). The F-105 seat was chosen as an operational standard for comparison. These and other hardware items used in the study are shown in Figures 1-4.

The dependent variables were selectively defined to provide quantitative data on relative body position with respect to the seat catapult thrust line and on intrinsic spinal curvature. Spinal flexion refers to a reduction in lumbar lordosis (including frank reversal of the lumbar curve). Spinal extension refers to an increase in the lumbar lordosis. The included angle refers to the acute angle between the catapult thrust axis and a line tangent to the thoracic and sacral convexities of the back at the body surface. The pelvic angle refers to the acute angle between a vertical reference axis and a straight line defined by the sacral promintory and a point located on the anterior margin of the sacrum 2.5 cm caudad to the sacral promintory.

A measure of each dependent variable was obtained from roentgenometric lateral views of the thoraco-lumbo-sacral spine of each subject postured in a particular seat/equipment geometry. The anterior superior margin of each vertebral body (including T6-8 through the sacrum) was identified, localized quantitatively, and plotted on graph paper.

Nine subjects used for this investigation were selected from the Vibration and Impact Hazard Duty Panel. Insofar as was possible, representative 5, 50, and 95 percentile sitting height individuals were included for each phase of the study in order to estimate the interaction of subject stature with the hardware design features. Two volunteer subjects that participated in the

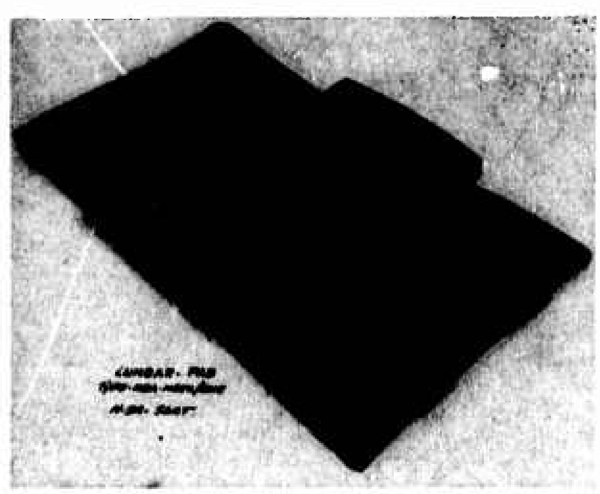

Fig. 3. 2.5 cm thick lumbar pad.

study were F-4 pilots. The subjects were measured for sitting height. Lead markers were taped on the skin between each of the spinous process of T6 through L5, on the posterior sacral convexity, and over the sacrococcygeal joint. After the subject had assumed the specified "tech order" ejection posture, the seat bucket (F-4 seat only) was adjusted where possible to bring the lateral canthus of the eye on the "optimum 15° over the nose" cockpit layout eye point. In the case of the larger subjects (greater than 50 percentile sitting height), it was not possible to bring the eye point to the specified location even with the seat full down; hence, the full-down position was used in this group.

Two subjects, the F-4 pilots, were deliberately postured to accentuate and assess the effect of forced submarining of the pelvis on intrinsic spinal alignment. For this particular study a prototype seat was used that employed a slightly different parachute pack, lap belt, and seat cushion from those present on the H-5 seat; however, these differences did not significantly affect the result.

The roentgenometric investigation was accomplished using a Picker clinical X-ray unit provided by the Radiology Service of Wright-Patterson Hospital, Wright-Patterson AFB, Ohio. All linear and angular distances between subject, anode, and film were measured with metric-tape, plumb-line, and transit so as to insure accurate repeatability.

The roentgenometric technique was designed to minimize parallax errors, accentuate image quality for vertebral structures, and limit subject X-ray exposure to safe levels. Parallax error, in general, decreases as the ratio of the film subject distance to the anode subject distance decreases. In theory, the parallax correction can be calculated exactly for any designated plane projected on any arbitrary film image plane; however, the calculation can be fairly laborious in practice unless certain simplifications are accepted. For example, the finite thickness of the vertebral bodies and the slight "built-in" inclination of the clinical X-ray cassette-holder (approx. 3.5°) produce small location-sensitive variations in the true parallax correction for any object plane. It was possible to neglect these effects without introducing any error greater than 1 per cent simply by restricting the maximum value of the ratio of the subject-film distance to the anode-subject distance to values less than 0.5. For ease of data reduction, the image of a piano-wire grid with approximately 3 cm horizontal and vertical spacing was superimposed on each film. A master calibration for image size was obtained by placing a metal calibrated rule precisely in the sagittal plane of the seat. The ratio of the object size to the image size for the calibration rule provided an accurate measure of the mean parallax correction for all midline structures of any subject properly postured in the seat. In this manner, the true dimensional relationships of the vertebral segments and midline surface markers could be calculated from the X-ray film record.

Fig. 4. 7.5 cm thick lumbar pad.

The image quality possible under the required experimental conditions was at best less than that of the usual clinical spine series. This was largely a result of the unusually large but necessary subject film distance and the presence of interfering hardware structure. It was not possible to use a free cassette in closer proximity to the suspect's torso, since without the bucky technique, film quality was completely unacceptable. Experience established the average exposure values for best results at 120-125 kv, 100-200 ma, 0.5-1.0 sec, 3 mm Al filtration, with an anode to spine distance of 104-120 cm and a spine to film distance of 30-52 cm. Ansco film automatically processed by a Pako Processor, Model 4, proved to be adequate, though some improvement of image quality might have been possible with a more tedious hand development procedure.

For the exposure parameters used, the skin dose per spine series was less than 3.0 r. No subject was permitted to receive more than 24 r cumulative skin dose. The X-ray beam was in all cases collimated to fill the film area only.

RESULTS

The subject population selected for the two primary aspects of this study were categorized according to sitting height. The number of subjects small in stature (less than 35%) was limited; however, good representation in the 35, 50, and 95 per cent groups was obtained. Table II presents the subject sitting height measurements for each experimental group.

TABLE II

F-105/F-4 Seat Comparison		Equipment Comparison	
Subject	% Sitting Height	Subject	% Sitting Height
AK	5	K	25
KW	49	H	34
RZ	50	B	35
WG	94	VH	35
PT	95	DC	35.5
		L	43
		RZ	50

STANDARD EJECTION POSTURE

The F-105 egress system was chosen as typical of all other Air Force egress systems in that the back rest is parallel to the catapult thrust axis. Five subjects were x-rayed while seated and restrained in the F-105 seat. Figure 5 presents graphically the data from four representative subjects showing the measured locations of the anterior superior margins of the vertebral bodies, T6 through L5, as well as the sacral promintory. The figure reveals that the vertebral column is aligned essentially parallel (within 5°) to the catapult thrust axis. The lordotic and thoracic curves are minimized. The variation in alignment and spinal curvature exhibited within this subject group is relatively small; however, a characteristic range of typical spinal geometries is demonstrated. Subject RZ presents a vertebral extension pattern, whereas subject WG presents a vertebral flexion posture. Subjects KW and PT present an intermediate pattern. The observed spinal configuration for each subject in the F-105 seat serves as the reference standard for comparative evaluation of the other seat/equipment geometries under study.

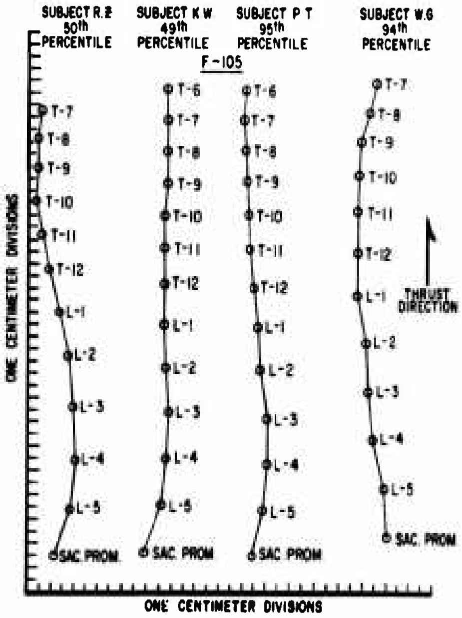

Fig. 5. Spinal configuration—F-105.

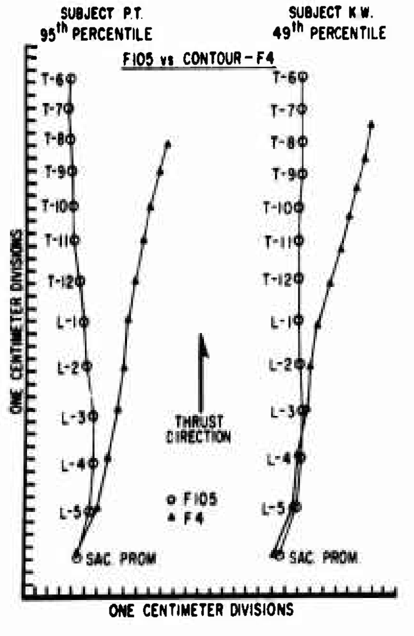

Fig. 6. Spinal configuration—F-105 vs contour RF/F-4C.

COMPARISON OF EJECTION POSTURES IN THE F-105 AND F-4 EGRESS SYSTEMS

The individual subjects X-rayed in the F-105 seat were also X-rayed in the H-5 model RF/F-4C seat employing the 7.5 cm thick contoured lumbar back pad used operationally in the Air Force since mid 1966. The principal difference in geometry between the F-105 and F-4 seats lies in the seat back-thrust axis divergence and the seat bucket-seat back angle. The F-4 seat back consists of a stationary upper wedge comprising the personnel parachute pack and a lower movable portion structurally united to the adjustable seat bucket. The F-4 seat back-seat bucket angle measures approximately 115°, whereas for the F-105 seat this angle is approximately 97°. Figure 6 presents the measured vertebral locations for subjects PT and KW plotted so as to provide direct comparison of the influence of the two seat geometries on spinal alignment. With these two subjects the included angle for the F-4 posture is approximately 12°, whereas the included angle for the F-105 posture is well within 5°. In addition, the F-4 configuration results in significantly more spinal flexion with the primary effect being straightening of the normal lumbar lordotic curve. The same trend effects were confirmed in all subjects examined.

COMPARISON OF EJECTION POSTURES MODIFIED BY EQUIPMENT DESIGN

Efforts to improve both comfort and the pre-ejection posture of aircrew using the RF/F-4C egress system

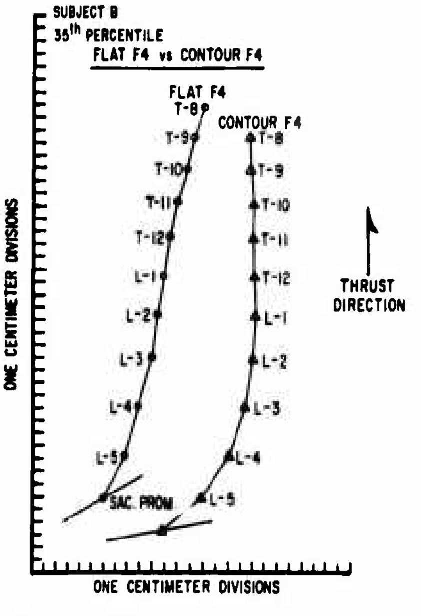

Fig. 7. F-105 flat vs contour RF/F-4C.

have resulted in several back-pad designs for filling the hollow below the wedge-shaped parachute pack. Prior to 1966 a 2.5 cm flat lumbar pad was used operationally by the Air Force; however, during 1966 this pad was replaced by a 7.5 cm thick contoured back pad. Five subjects were X-rayed in the RF/F-4C seat employing both pad designs. One subject (RZ) in this group had been previously x-rayed in the F-105 seat, as well. Figure 7 shows the spinal alignment of subject RZ for each of the three seat/equipment configurations.

Although this subject exhibited an extended column in the F-105 seat, his spine is definitely flexed in the F-4 seat when the 2.5 cm flat pad is employed. The flexion displacement has brought the average back line forward 14°. The introduction of the 7.5 cm contoured pad significantly modifies both the spinal alignment and the spinal location in relation to the seat survival kit lid contour. Spinal alignment is generally improved. The degree of flexion is significantly less and the included angle is reduced by approximately 6°. Equally significant is the observation that the sacral promintory is shifted 5.5 cm forward and 2.5 cm downward. This fact implies that the ischial tuberosities have been positioned to coincide more closely with the concavity of the seat cushion/survival kit lid contour.

Figure 8 presents data demonstrating that individual subject factors can strongly influence the modifying effect of a particular equipment design. For subject B, the 7.5 cm contoured pad appears to over-correct the spinal curvature deviation seen with the 2.5 cm flat pad. The spine exhibits fairly good intrinsic alignment with the thin pad, although the included angle is large, being approximately 16°. The 7.5 cm contoured pad, however, exaggerates the spinal extension resulting in an undesirable degree of lumbar lordosis. This effect is also seen in the large amount of pelvic rotation. The pelvic angle is increased by approximately 18°. The end result is a thoracic spine that is fairly well aligned with the thrust axis, but a lumbar spine and pelvis that is sharply angled by as much as 50° with the thrust line. As in the case of subject RZ, the forward and downward shift of the sacral promintory is again observed.

For each of the observations reported above, the subjects were instructed to assume and hold a "tech order" posture. In an effort to obtain order of magnitude information about the influence of operational practice as well as restraint harness interaction on pre-ejection posture, the assistance of two Air Force flight test pilots was solicited. These two individuals (subjects C and VH) were asked to assume a normal flight posture using a lap belt tension that in their opinion could be considered standard practice. Without benefit of preinstructions, each subject was commanded to assume his "normal" ejection posture and to actuate the D-ring. Figures 9 and 10 present the spinal position

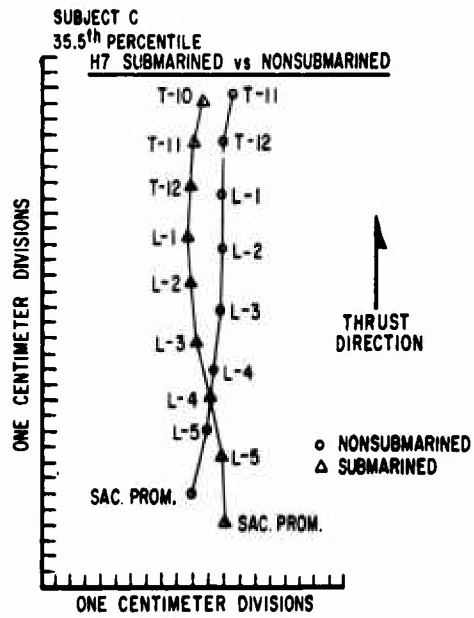

Fig. 9. H-7—submarined vs non-submarined.

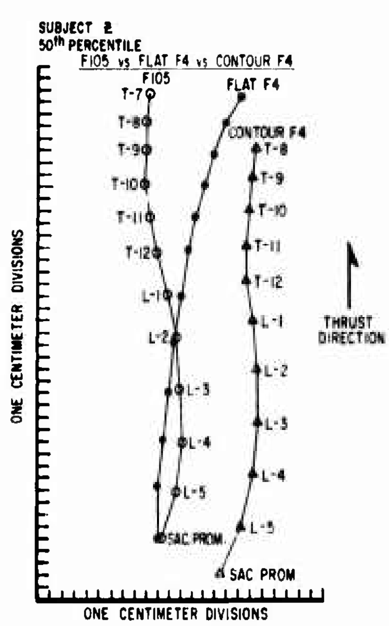

Fig. 8. Flat vs contour RF/F-4C.

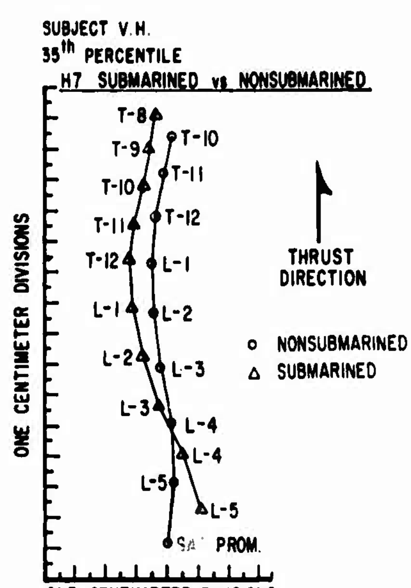

Fig. 10. H-7—submarined vs non-submarined.

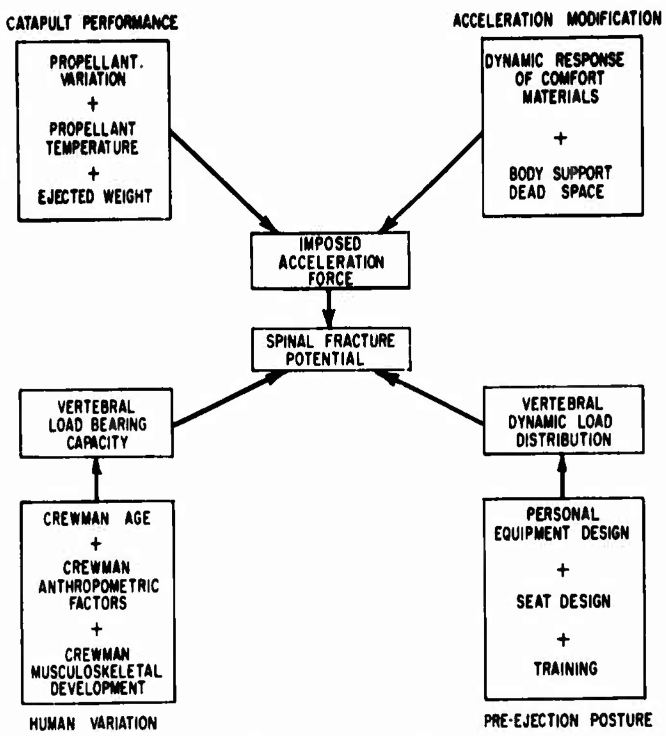

Fig. 11. Factors contributing to risk of spinal fractures during ejection.

data obtained from X-ray views taken under these conditions. The vertebral alignment of both subjects is noticeably atypical compared to the alignment found for the panel subjects who had been instructed to assume the tech order posture. The pilot subjects exhibited fairly good postural geometry with relatively small included angles (0° and 6°). On the other hand, the restraint afforded by the lap belt permitted considerable pelvic mobility. When each subject was forcibly submarined by applying moderate traction to his legs, flexion of the spine and anterior displacement of the sacral promintory occurred. The included angle was actually reduced to less than zero. The normal weight bearing column of the spine is obviously subject to considerable realignment in spite of a "normally" tensioned restraint harness. The actual spinal alignment at the time of ejection cannot be assumed to be that produced by the tech order posture.

DISCUSSION AND CONCLUSION

The spinal column is the primary load transmitting element supporting the torso, head, and shoulders during exposure to ejection forces. Bosee[6] demonstrated that the vertebral bodies are located squarely over each other when the normal seated posture is maintained. This optimal alignment affords equal distribution of compressive force over the full load bearing surface of the vertebrae. Any deviation of the normal intervertebral alignment increases the likelihood of load concentration on the affected vertebra, increasing the potential for compression fracture. Bosee[6] further noted that spinal flexion is particularly undesirable since the accompanying anterior shift in the location of the CG of the head and upper torso promotes additional flexion of the lumbar spine during dynamic loading.

The foregoing considerations emphasize the importance of body position in the genesis of spinal fractures occurring during ejection. Figure 11 presents a flow chart defining the inter-relationship of the several causal factors contributing to the risk of spinal fracture during ejection. The effect of seat/equipment design can only be adequately evaluated in context with the other contributing factors. Since this analysis generally requires a full scale dynamic test program, it is clear that a static investigation of posture can lead at best to conditional conclusions. Nevertheless, the results of this study do permit the following summary inferences for the RF/F-4 egress system:

1. Within sample limits, a significant relationship of anthropometric dimensions to spinal position is not established.
2. Spinal misalignment in the F-4 seat (H-5) can be as great as 14° forward of the catapult thrust axis.
3. Spinal curvature is significantly altered by the F-4 seat back pad design.
4. Submarining of the pelvis induces lumbar flexion.
5. The existing F-4 seat lap belt/seat pan design can permit increased spinal flexion under dynamic loading.

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