High-Risk Head and Neck Movements at High G and Interventions to Reduce Associated Neck Injury

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Background: Neck injuries are a significant concern for aviators of high performance aircraft. A recent comprehensive technical report on cervical spinal injury associated with exposure to sustained acceleration, from NATO's Research and Technology Organization, recommended delineating the neck muscles used by aviators in this flying environment and developing improved neck muscle strengthening programs in an attempt to reduce such injuries. ***Methods:*** A review of current literature was conducted in the fields of biomechanics, ergonomics, orthopedics, neurology, neurosurgery, rehabilitative medicine, and aerospace medicine. An objective description is provided of the muscles involved in specific head and neck movements, and those movements that are associated with a greater risk of injury during high-G sorties. The intensity and duration of force exposures common to high performance aircraft sorties, the effects of seat-back angle on these exposures, and the types and mechanisms of neck injury reported in this environment are also described. ***Results:*** Primary, secondary, and tertiary preventive interventions are introduced with the goal of providing unit-level flight surgeons an approach to reducing neck injury and promoting prompt, safe return to flying of aviators with identified neck injury. A central component of these interventions is a "specific" and "intensive" neck muscle training regimen, as described in the medical literature. ***Conclusion:*** Increased axial compressive force and unique biomechanics combine to make neck injury likely in high performance aviators. The application of some proposed intervention strategies may reduce the occurrence of these injuries.

Keywords: aerospace medicine, biomechanics, neck muscles, occupational exposure, cervical spinal injuries, neck injuries, prevention and control, rehabilitation.

KNOWLEDGE OF cervical spine movement, function, and tolerance limits is essential in designing programs to reduce or mitigate injuries resulting from exposures to high performance aircraft flight profiles. This review paper considers the function of the components of the cervical spine, their actions in spine movements, use of previously developed static and kinematic models in determining the functional limits of the spine, forces acting on the spine in the flight environment, types of injuries, and application of the information in designing injury risk reduction strategies.

Basic Neck Biomechanics

Functional Roles of Neck Structures

It is useful to divide the structural components of the neck into hard tissues and soft tissues (6). The hard tissues include the vertebrae and intervertebral disks, which function primarily in a load-bearing role in which they resist compressive forces. The soft tissues include ligaments and muscles that serve to stabilize and support the hard tissues by resisting tensile forces, and also provide for movement.

Vertebrae: Those vertebrae that are separated by intervertebral disks are functionally grouped into three divisions, the cervical (C1-C7), the thoracic (T1-T12), and the lumbar (L1-L5). Together with the sacrum and coccyx, they provide axial support for the body. Within these three functional groups, the relatively small size of each bone and the number of individual bones joined by flexible, but strong, connections (i.e., the intervertebral disks and ligaments) allows for great flexibility in addition to excellent load-carrying capacity.

Intervertebral disks: The disk is composed of three major components (40): 1) two cartilaginous plates; 2) the nucleus pulposus, and; 3) the annulus fibrosus. The cartilaginous plates serve to separate the disk from the vertebral bodies above and below the disk. The nucleus pulposus is an oval gelatinous mass made up of chondrocyte-like cells in an intercellular matrix which has a fairly dense network of poorly differentiated collagen fibrils, each covered with a polysaccharide-protein complex which binds water. The nucleus is 75–90% water by weight, is located in the center of the disk, and takes up 50–60% of the cross-sectional area of the disk. The role of the nucleus is to maintain the height of the disk (40).

The annulus fibrosus is composed of layers of collagenous tissue and fibrocartilage with the fibers oriented obliquely to give the disk its elasticity. The fibers in adjacent layers are oriented approximately perpendic-

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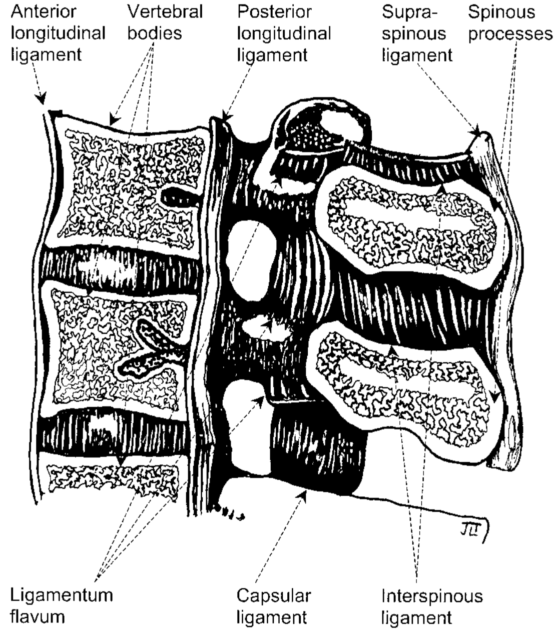

Fig. 1. Section through the vertebrae showing selected ligaments. Fig. 1 was adapted (redrawn) from source illustrations contained in *Anatomy of The Human Body* by Henry Gray, F. R. S., 21st edition by Warren H. Lewis, B. S., M. D., Illustrated with 1283 Engravings.

ularly to each other. The annulus is firmly anchored to the adjacent vertebrae, and is twice as thick in the anterior and lateral portions as it is in the posterior portion. The fibers of the innermost layer of the annulus pass into the nucleus pulposus and blend with its intercellular matrix, and thus, no distinct demarcation exists between the annulus and the nucleus. The annulus fibrosus is the primary load-bearing component of the disk. The viscoelastic behavior and stiffness of the disk is determined by the annulus (40).

Ligaments: Multiple ligaments are located along the length of the spinal column. These include (among others) the supraspinous, the interspinous, the anterior longitudinal, the posterior longitudinal, and the ligamentum flavum. The ligaments function primarily to stabilize and support the vertebrae and disks (6,33,39,73). Their relative positioning is shown in **Fig. 1**.

Muscles: There are more than 40 muscles, paired and symmetrical to the mid-sagittal plane, attached to the cervical spine (38). These muscles act on 37 joints to produce the extensive range of neck movements. The neck muscles do not act along straight lines, but rather are groups of functional subunits with several lines of action (42). **Fig. 2** is a representation showing the relative locations of the major neck muscles discussed below.

Active (i.e., muscular) forces interact with gravity and passive ligamentous forces to both stabilize and move the head (44). However, the inherent function of the neck muscles in man is not completely understood, due in part to the redundancy of the muscle groups found (10,11). Several studies (10,20,38,44,45,48) have shed light on the contribution of the various muscles to neck movement. An understanding of these functional roles provides a framework for considering neck injury treatment and prevention. **Table I** contains a summary of the major muscles involved in movements of the head and neck.

Normal C-Spine Movement

A 1978 radiological study (60) of the normal cervical vertebrae movements demonstrated that the C-spine functions as a unit from C3-C7—every muscle activating several segments at once—and movement occurs in a coordinated fashion throughout the individual segments. However, the degree of mobility in each segment varies. The segment with maximum mobility in flexion-extension from C3 to C7 is the C5-C6 segment (16–29°) (37,60). This segment is followed in decreasing order by C4-C5 (15–29°), C3-C4, and C6-C7 (60). Of the entire C-spine, the segments that have the greatest range of motion (ROM) in flexion-extension are occiput-C1 and C1-C2. Of note, the greatest ROM in rotation in the entire C-spine is found at the occiput-C1 level.

Extension: The major muscles involved in active neck extension are the splenius capitis, semispinalis capitis and cervicis, and multifidus muscles (10,11,44,48). These muscles have been shown to hypertrophy 24–25% in response to neck extension exercises (11). Also contributing is the levator scapulae, longissimus capitis and cervicis, and scalenus medius and anterior (11,48). Passive extension of the neck and resistance to forced extension can also occur, and is controlled by the neck flexors (10,44).

Flexion: The bilateral components of the sternocleidomastoid muscle provide the main active force in flexion (10,44,48). Other muscles shown to contribute to active flexion include the longus capitis and colli (10,44,48). During partial flexion, with straightening of the cervical lordosis, the longus colli muscle has been observed to

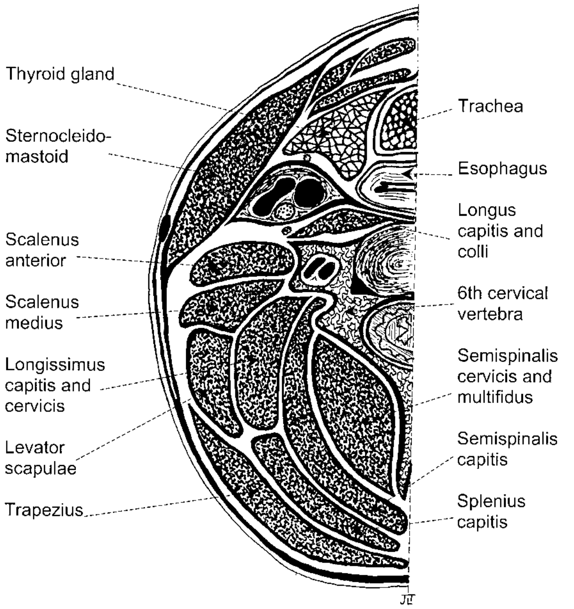

Fig. 2. Cross-section of the neck at the level of C6, highlighting the relative positions of selected muscles. Fig. 2 was adapted (redrawn) from source illustrations contained in *Anatomy of The Human Body* by Henry Gray, F. R. S., 21st edition by Warren H. Lewis, B. S., M. D., Illustrated with 1283 Engravings.

TABLE I. MUSCLES INVOLVED IN HEAD & NECK MOVEMENT*.

Extension	Flexion	Lateral Bending	Resistance to Forced Lateral Bending	Axial Rotation
Splenius capitis (10,11,44,48) Semispinalis capitis (10,11,44,48) and cervicis (10,11,48) Multifidus (10,11,48) Levator scapulae (11,48) Longissimus capitis and cervicis (11,48) Scalenus medius and anterior (11,48) Transversospinalis (44)	Bilateral: Sternocleidomastoid (10,44,48) Longus capitis and colli (10,48)	Ipsilateral: Sternocleidomastoid (10,48) Splenius capitis (44,48) Semisplenius capitis (44,48) Transversospinalis (44)	Contralateral: Sternocleidomastoid (38) Levator scapulae (38) Semispinalis (38)	Ipsilateral: Splenius capitis (10,44,48) Levator scapulae (10,48) Scalenus (10,48) Semispinalis capitis (10,44,48) Contralateral: Sternocleidomastoid (10,44,48) Semispinalis capitis (10) "Recruitment" phenomenon (10)

* Muscles shown in descending order of contribution to movement.

be activated, while the splenius capitis, semispinalis capitis, and the transversospinalis muscles are all deactivated (44). Due to the center of gravity of the head being forward to the ear, and thus anterior to the axis of the C-spine, passive flexion of the neck and resistance to forced flexion can occur, and are controlled by the extensor muscles (44).

Lateral bending: Active lateral bending is mainly a function of ipsilateral (i.e., located on the same side) sternocleidomastoid contraction (10,44,48). The ipsilateral splenius capitis, semispinalis capitis, and transversospinalis muscles have also been shown to play a role (44,48). Resistance to forced lateral bending has been shown to involve the contralateral (i.e., located on the opposite side) sternocleidomastoid, levator scapulae, and semispinalis muscles (38).

Axial rotation: Neck rotation involves the largest number of different muscles. These include the ipsilateral splenius capitis, levator scapulae and scalenus, and the contralateral sternocleidomastoid (10,44,48). Both the ipsilateral (48) and the contralateral (10) semispinalis capitis have been shown to be involved as well. Trapezius participation is negligible (43). During neck rotation, it appears that increases in force are achieved by recruitment of previously unused muscles, in addition to recruitment of additional motor units of the same muscle and increased motor neuron firing frequency (10). For example, activation of the semispinalis capitis muscle has been observed to occur only during intense neck rotation (10).

A meta-analysis of 45 studies (9) showed that women generally have greater ROM than men and that ROMs decrease with age at about 4° per decade after the third decade. However, results from individual studies vary in this regard (37,41). The biomechanical characteristics associated with flexion, extension and rotation of the neck are summarized in **Table II**.

C-Spine Models

Sagittal plane model: The 1978 sagittal plane C-spine model describes the equilibrium force at each intervertebral joint as a balance among four component forces: 1) the external load; 2) the reaction force of the joint acting at the center of the reaction; 3) the muscle tension acting about the center of the reaction, and; 4) the ligament tension acting about the center of reaction (28). The model has been used to determine the maximum acceleration load that can be supported by the neck in varying degrees of flexion and extension, compared with the neutral position.

Kinematic model: In this model (67), the investigators built on the normal C-spine movements defined in the previously described sagittal plane model (60). The model forms a kinematic chain with eight links, each with six degrees of freedom. The connecting joints restrict the degrees of freedom and the amount of motion. Some simplifications are made in the model: 1) the axes of rotation are assumed to be located in the middle of the respective joints, and; 2) the lower C-spine (C3-C7) is considered as a single link, and intrinsic forces in this part of the spine are not incorporated into the model.

Our review failed to reveal a study which describes the actual forces present in these lower C-spine segments during high performance flight. However, the magnitude of the forces within this region can be implied from the calculated forces at C7-T1. Since most neck injuries in high performance aviators occur at levels between C3-C7, and not at C7-T1, it may be valuable to accurately describe the forces present in the individual segments of the lower C-spine via future studies.

Tolerance Limits of Neck Structures

An extensive body of literature exists regarding the physical limits of the hard and soft tissues of the human neck from cadaveric specimens (33,39,40,73–77,79) and healthy volunteers (34,43,45,62) subjected to compressive, shear, and tensile force. A summary of these tolerance limits is presented in **Table III**.

Variation of C-Spine Posture from Neutral

Biomechanical models demonstrate a rapid decrease in the ability to support the cervical spine and head under high loads when position varies from the neutral,

TABLE II. C-SPINE CHANGES WITH NECK MOVEMENT.

	Spinal Canal Sagittal Diameter*	C5, C6, C7 Neuroforamina Diameter*	C5, C6, C7 Neuroforamina Pressures*	Other Information
Partial Flexion (15–20°)				Straightening of lordotic curve (33,63,67,73) “Stiffest axis” (63)
Flexion (>20°)	Up to 13.9% (8)	8–10% (78)	Mod. ↑ @ C5 & C7 (14) Slight ↓ @ C6 (14)	Spinal canal sagittal diameter the greatest (8) Anterior compression of disc (39) Rearward internal pressure in disc (39)
Extension	Up to 22.7% (8)	10–13% (78)	↑ ↑ (14)	Spinal canal sagittal diameter the smallest (8) Least tolerance for reduction in diameter @ C5–C7 (8)
Axial Rotation		↓ ipsilaterally (78) ↑ contralaterally (78)		
Flexion + Axial Rotation		↓ widening ipsilaterally (78) ↑ widening contralaterally (78)		
Extension + Axial Rotation		↑ narrowing ipsilaterally (78) ↓ narrowing contralaterally (78)		

* Compared to the neutral position.

upright position due to cervical flexion, extension, and rotation (12,67). This is consistent with the finding that the lever arm of a neck load depends on neck length and head position (45). Thus, as the lever arm increases during head and neck movement away from the neutral position, the moment increases and the muscle and ligament forces required to support these structures likewise increase.

Using the sagittal plane model, it has been shown that the maximum acceleration load, applied along the x axis, that can be supported by the neck, drops from $+30\ G_z$ in the neutral position to $+24\ G_z$ when the neck is fully flexed, and to $+15\ G_z$ when the neck is fully extended. This change occurs rapidly with minimal movement from the neutral position. The authors concluded that, in the neutral posture, the muscles are most effective in supporting the load because the moments that have to be supported in this posture are smaller, and because the muscles have a better mechanical advantage.

In a study of isometric contraction force of the neck extensors (43), with the neck in the neutral, extended, and flexed positions, the maximum force generated and the greatest muscle efficiency were found in the neutral position. For example, in a study of human cadaveric preparations (39), when C-spine flexion or extension reached 25° from neutral, it required a 50% lower load to produce failure (i.e., the load at which bone, disk, or ligament disruption occurred).

Application to the High Performance Flying Environment

The high performance flying environment involves forces of high intensity (occasionally greater than $+9\ G_z$). Forces above $+4\ G_z$ have been associated with the potential for neck injury (6,19,21). Most surveys have reported symptom onset in the $+4$ to $+9\ G_z$ range (2,13,24,36,52,64). Data gathered during $+G_z$ force exposures during Air Combat Manuvers (ACM) in the F/A-18, the Hawk 51 or 51A, and the F-16 are summarized in **Table IV**. Although individually of short duration, in ergonomic terms these additive exposures represent the known work-related musculoskeletal disorder (WMSD) risk factors of high force and high repetition. Such exposure profiles may lead to higher demands for maximum muscle strength and muscle endurance in fighter pilots than in the general population (57).

Forces Acting on the C-Spine

As described in the Sagittal Plane model (28), the forces acting on the C-spine in high performance flying can be broken down into compressive, tensile, and shear components. These components result from the acceleration and vibration-induced forces present in the cockpit environment (15). We will use standard references to axes of force with regard to the human body in this article. These include the x axis (i.e., forward-backward), y axis (i.e., right-left), and z axis (i.e., up-down).

Acceleration: Consistent with Newton’s third law of motion, aircraft acceleration produces inertial forces (G). These forces are a function of the magnitude and direction of the acceleration and the mass of the accelerated object. They occur in the x, y, and z axes (G_x, G_y, G_z) in reaction to the acceleration and opposite to its direction. With regard to the pilot’s upright, seated body, $+G_x$ is directed from anterior to posterior (i.e.,

TABLE III. C-SPINE TOLERANCE LIMITS.

Component	Maximum Load	Male vs. Female	Maximum Isometric Force-Generating Capacity	Isometric Contraction Endurance Time @ 90% MVC	Additional Information
Vertebrae	(Compression) Overall: 1.56-7kN (63) Males, 3rd decade: 7 kN (63) Males, 9th decade: 2 kN (63)	Males have 25% greater compressive load tolerance (63)			Loading rates have a greater effect at younger ages (63)
Intervertebral Discs	(Compression) (40) Over 400 kg (symmetrical load)				
Anterior Longitudinal Ligament	(Tension) (74) Load Rate — Max Load 8.89 mm/s — 120.58 N 2500 m/s — 349.48 N				
Ligamentum Flavum	(Tension) (74) Load Rate — Max Load 8.89 mm/s — 130.64 N 2500 m/s — 335.07 N				Energy required to cause spinal instability without fracture = 30 J (74)
Extensor Muscles	(Moment) (34)* 65.1 Nm (males) 53.4 Nm (females)		Extensors greater than flexors (34,48,49) 10.17 N/cm^2 ratio of max. isometric contractile force to muscle cross sectional area (45)		Extensors 1.7 times stronger than flexors for both males and females (34)
Flexor Muscles	(Moment)** 36.5 Nm (males) (34) 32.4 Nm (females) (34)		Flexors greater than rotators (6,10)		
All Muscles		3rd to 6th decades: males 20–25% stronger (34) 7th decade: females stronger (34)	Greatest in neutral neck position (43)	Dorsal muscles greater than lateral muscles greater than anterior muscles (62)	Cervical muscle has approximately twice the maximum strength, relative to weight, as lumbar muscle. (34) Fatigue Index of 2.0–2.1 in posterior and lateral muscles (58)
Whole Neck	— Accel. Load (28): — Failure Load (39): Neutral — +30Gz — 100% Flexion — +24Gz — 50%*** Extension — +15Gz — 50%****				

* @ 15–60° extension ** @ 45° flexion *** @ 25° flexion **** @ 25° extension

through the chest to the back) and $+G_z$ is directed from superior to inferior (i.e., toward the feet). $+G_y$ is directed laterally, from left to right.

Positive and negative G_x forces result in bending moments about the y axis (i.e., flexion and extension) and x-axis shear (72). With the frequent and forceful banking and rolling performed in flight, resulting in positive and negative G_y forces, bending moments about the x axis (i.e., lateral bending) and y-axis shear forces are also anticipated. These y-axis shear forces are expected to be of significance. However, to our knowledge, the in-flight magnitude and effects of these lateral forces have not been documented.

Forces acting along the z axis are of most importance with respect to adverse effects on the cervical spine. Positive G_z forces cause spinal compression. This compression is also manifested as varying shear components at each level of the C-spine, largely due to the orientation of the facet joint articulations (76,79).

Shear forces are also associated with neck movements. One study (48) used a computer model to calculate the resulting mean shear and compressive forces at the C4-C5 level associated with maximum voluntary contractions (MVC) of the various neck muscles during active flexion, extension, and lateral bending at $+1\ G_z$. Calculated shear forces along the x axis ranged from -2 N (-0.45 lbs) in the neutral, relaxed position to 135 N (30.35 lbs) in extension. Calculated shear forces in the y

TABLE IV. +GZ EXPOSURE DURING ACM.

Aircraft	Sortie Total Duration	Number of Excursions Above +2 Gz	Average Time per Excursion Above +2 Gz	Total Time Above +4 Gz*	AverageNumber of Excursions Above +4.5 Gz	# of Peak Strain Episodes of Posterior Neck Muscles	# of Peak Strain Episodes of Lateral Neck Muscles
F/A-18 #1 (55)	33.6 min	37	8.3 sec. (1–35 sec.)	1.2 min. (3.7%)			
F/A-18 #2 (55)	53.9 min	61	7.8 sec. (1–41 sec.)	2.3 min. (4.4%)			
F-16 (31)				(49% @ less than +2 Gz) (5% @ greater than +7 Gz)			
Hawk 51 or 51A (58)	Avg: 30 min Range: 26–36 min				38 (Range: 25–55)	Range: 10–18	Range: 10–85

* And % of Total Sortie Time Above +4 Gz (in parentheses).

axis ranged from 0 N in extension, flexion, and the neutral, relaxed position to 125 N (28.10 lbs) in lateral bending.

Shear forces are increased as aircraft accelerations occur simultaneously in more than one axis. As a turning F-16 undergoes positive acceleration in the z axis, it simultaneously experiences negative acceleration in the x axis approximately according to the following relationship: $A_x = -0.12\ A_z\ (ms^{-2})$ (31). This finding confirms that increased $+G_z$ is associated with x-axis negative acceleration in this setting. This negative acceleration adds to the x-axis shear component already generated by the spinal compression resulting from $+G_z$. With higher compressive forces, caused by greater $+G_z$, much larger shear forces within the C-spine would be expected.

Cervical spine shear forces are counteracted by the intervertebral disk-vertebral body connections and by the supporting ligaments and muscles. Injury to these structures could result from excessive shear forces alone. With the advent of vectored thrust technology, which someday could add a lateral force component, shear may become even more of a concern (53).

Vibration: Vibration is defined as "any sustained, mechanical, oscillatory disturbance perceived by senses other than hearing" (25). It can be considered as a special case of acceleration, where force vectors are repetitively and rapidly changing. This leads to compressive, tensile, and shear force effects on the spinal column. Although vibration exposures are less in fighter aircraft than in helicopters, attenuation of adverse vibratory forces may play a role in minimizing chronic degenerative changes of the C-spine in high performance aircraft aviators.

High-Risk Movements

Certain neck movements, by the nature of their biomechanics, cause high joint reaction forces, require high forces in the supporting muscles and ligaments, create compromised cervical geometry, and are associated with the occurrence of reported neck injury during high performance flight. The compromised cervical geometry refers to spinal canal narrowing, neuroforaminal narrowing and pressure increases, intervertebral disk compression and twisting, increased intradiscal pressures, and awkward alignment of the vertebrae that disrupts the normal transfer of forces from one level to the next. These factors combine with the high forces present to set the stage for increased risk of neck injury. In this section, neck biomechanics and cervical geometry are used to objectively define the more high-risk head and neck movements.

In the high performance aviation environment, these movements can take place in an almost constantly changing, dynamic fashion. However, with regard to the relative muscle capacities and tolerances, some of the data used in this analysis comes from isometric (laboratory) measurements, while other data comes from dynamic (in-flight) measurements. Although the isometric data would be expected to be consistent with the in-flight data, there may be incompatibilities between the two data sources. The following analysis is based on the premise that the two sources of muscle measurements are comparable.

Rotation Beyond 35°

Axial rotation of the neck requires minimal force up to about 35° of rotation, beyond which the muscular forces and joint reaction forces at C7-T1 increase very rapidly (67). Calculated joint reaction forces at C7-T1 increased by up to a factor of 15 when the neck was rotated under high $+G_z$ force in the F-16 (31). The neck rotator muscles have the least isometric force-generating capacity among the functional neck muscle groups (10).

Axial rotation, combined with flexion, has a diminutive effect on neuroforaminal widening ipsilaterally, and an additive effect on widening contralaterally. Conversely, in combination with extension, axial rotation has an additive effect on neuroforaminal narrowing ipsilaterally, and a diminutive effect on narrowing contralaterally (78). Acute nerve compression injury may thus be a result of forceful hyperextension in combination with ipsilateral rotation (78).

Exacerbated effects of these factors would be expected in the high performance flying environment with the increased $+G_z$ forces. Indeed, acute neck injuries in pilots of fighter aircraft frequently occur in association with rotated neck postures (2,6,19,35,36,52,64,69).

Lateral Bending

A dramatic increase in joint reaction forces at C7-T1 and in the supporting muscles occurs with lateral bending of the neck beyond 0° (67). Although the specific head and neck positions were not identified during these in-flight measurements, the calculated values (31) in the sternocleidomastoid and trapezius muscles and the MVCs (57) of the "lateral neck muscles" (specific muscles not identified) have been reported to be the highest among the different muscle groups. Also, the "lateral neck muscles" were shown, in one study involving four male subjects, to have less isometric endurance at 40% MVC and above than the dorsal muscles (62). Lateral bending in combination with rotation and axial compression also leads to significant strain on the intervertebral disk (14). In addition, y-axis shear forces have been shown to significantly increase with lateral bending at $+1\ G_z$ (36).

The optokinetic cervical reflex: Studies have shown that pilots naturally tilt their heads to the side during aircraft bank in an apparent attempt to align their eyes with the visible horizon in order to maintain spatial awareness (12,32,46,47,59,66). One study (46) has shown the same phenomenon among pilots of high performance aircraft, with the pilot tilting the head to a head-horizon orientation until reaching about 45° of bank. The same process occurs when rolling out of a steep bank, resuming a head tilt at about 45° of bank and maintaining it until returning to a "wings level" attitude.

This is important because, as noted earlier, lateral neck bending creates significant stresses on the neck structures. Reflexive lateral bending of the C-spine in response to aircraft bank under high $+G_z$ loads repeatedly exposes the pilot to this high-risk neck movement.

Extension Beyond 30°

When the neck is extended beyond 30°, as in looking directly overhead, joint reaction forces in C7-T1 rapidly increase, as do the required supporting muscle forces (67). Although the specific muscles were not identified, the isometric endurance time of the "anterior neck muscles" (activated to support the C-spine in extension) was reported to be the least of all the neck muscle groups (62). Also, x-axis shear forces have been shown to increase significantly with neck extension at $+1\ G_z$ (48).

In addition to these high forces, the sagittal diameter of the spinal canal decreases by as much as 22.7% during extension, compared with the neutral position (8). During extension, the diameter of the C5, C6, and C7 neuroforamina have an average decrease of 10%, and a decrease of 13% at 30° of extension (78). During extension, pressures within the neuroforamina are significantly increased at the C5, C6, and C7 levels, compared with the neutral position (14).

Flexion Beyond 15°

When the neck is flexed beyond 15°, joint reaction forces in C7-T1 rapidly increase, as do the muscle forces required to support the neck (67). The cervical extensor muscles (activated to support the C-spine in flexion) have the greatest isometric force-generating capacity among the major neck muscle groups (10). However, as previously noted, these muscles have decreased mechanical advantage, decreased force-generating capacity, and decreased efficiency with the neck in the flexed position (28,43). Also during flexion, pressures within the neuroforamina have been shown to moderately increase at the C5 and C7 levels and slightly decrease at the C6 level, compared with the neutral position (14). Many neck injuries in pilots of high performance aircraft are associated with flexed neck postures (6,19,35,64).

"Checking Six"

"Checking six," or looking directly behind the aircraft, requires maximal neck rotation from a fighter pilot. This requires maximal recruitment of muscle motor units (10). Unfortunately, the neck rotator muscle group has the least isometric force-generating capacity of all the neck muscles (10). At $+1\ G_z$ this is a strenuous task; adding the force required to stabilize the head and neck under high $+G_z$ makes the task particularly strenuous. The number of muscles involved, the intensity of contraction required, the limited force-generating capacity of the muscles during rotation, and the awkward posture involved, make this maneuver very high-risk for neck injury.

The "check six" maneuver often involves flexion or extension and lateral bending in combination with axial rotation (52). The strain on the cervical erector spinae muscles is greatest in rotation-plus-extension positions of the neck (20). This suggests that the capacity of the muscles to "protect" the structures of the cervical spine against the stress caused by high $+G_z$ forces is lowest in twisted positions where, in fact, most "protection" is needed (20). The "check six" maneuver often results in acute neck injuries in pilots of high performance aircraft (1,2,6,19,35,36,52,64,69).

Magnitude of In-Flight Forces

Joint Reaction Forces and Muscular Strain

The mass of the head varies between 3.5–5 kg (7.7–11 lbs) (64,77), which results in a gravitational force of approximately 34–49 N. With an additional 1.8–2.2 kg (4–4.8 lbs) of headgear (helmet, visor, mask, etc.), static load equivalents of 471–638 N (106–143 lbs) are generated at $+9\ G_z$ (64).

Actual in-flight forces have been estimated using measurements taken from helmet-mounted accelerometers and electromyograms (EMGs). One group (31) derived in-flight forces in the F-16 as a function of acceleration, using helmet-mounted accelerometer data. They then calculated the C-spine joint reaction forces and supporting muscle forces for accelerations in the x, y, and z axes, using the Kinematic model (67). The investigators used the F-16 measurements to calculate forces in the sternocleidomastoid and trapezius muscles and found that the forces neared the maximum strength (in cadavers) of 150 N (33.72 lbs) in these muscles. Other calculated joint reaction forces exceeded the least compressive force required to cause fractures in cadaver experiments.

A second study (57) used a surface EMG recording device to measure in-flight muscle activity calibrated relative to the percent of the individual's MVC, measured in the laboratory, prior to flight. The in-flight measurements were obtained from volunteer fighter pilots during one-on-one ACM exercises in Hawk MK 51 aircraft. The measured peak "lateral neck muscle" force in six pilots ranged from 50–257% MVC (mean: 84.8%). The pilot who generated the peak strain of 257% MVC suffered an acute neck injury which interrupted his flight.

A third study (20) measured the force in the "cervical erector spinae muscles" as a percent of the MVC. The measurements were obtained from fighter pilots while flying under specified conditions, with the head in predetermined positions, in Hawk MK 51 aircraft. Among the different subjects, when the pilot's neck was rotated and the aircraft was under a $+4$ G_z load, the peak muscle force ranged from 28.2–189.7% MVC, with a mean of 79.5%. With active movement from flexion to extension under a $+4$ G_z load, erector spinae muscle force ranged from 29.0–109.9% MVC, with a mean of 55.8%. The authors reported large differences in muscle force measured among the individual subjects.

Effect of Seat-Back Angle

Seat-back angle has an effect on the distribution of G-induced petechiae (70) and on subjective discomfort sensation in response to whole-body vibration (27). Sitting with a slight backward inclination of the thoracic-lumbar spine increases the risk of extreme positions of the cervical spine and C7-T1 disk pressure, due to the required flexion of the neck (26). The investigators found that in the flexed position, the load moment about the C7-T1 motion axis is increased 3.6 times the value measured in the neutral position.

A comparison of cervical spine biomechanics between the F-16 with a 30° reclined seat and other high performance jets with more vertically oriented seats (12–13°) can be made by using the data from one study (31) in which the Kinematic model (67) was used. This study found that an F-16 pilot required an additional 15° forward flexion of the neck with respect to the trunk in order to maintain a normal direction of gaze in relationship to the horizontal plane.

The required flexion resulted in decreased lordosis of the cervical spine, confirming the findings of other studies (33,63,67,73). The lordosis is considered important in maintaining stability during axial loading, and a decrease in the lordotic curve may lead to increased compressive forces in the spine and increased intradiscal pressure (3,26).

As previously mentioned, when the neck is in the neutral, upright position, the neck muscles have a better mechanical advantage (28) in addition to maximum force-generating capacity and greatest muscle efficiency (43). The added flexion of the neck required in the F-16 results in additional lengthening of the dorsal neck muscles. These muscles would be expected to have decreased mechanical advantage, decreased force-generating capacity, and decreased efficiency in the "F-16 position." This results in decreased ability to stabilize the spine and support the head in the high-G flying environment (up to $+9$ G_z in the F-16). Similar effects on the ligaments would be expected.

Flexion also causes increased anterior pressure on the intervertebral disks, which results in increased rearward pressure on the posterior annulus fibrosus, from within the disk (26,39). These factors could explain why the F-16 pilot may be at greater risk than other high performance aviators for both acute and chronic neck injury.

Occupational Neck Injuries in Pilots of High Performance Aircraft

Acute Injuries

Under experimental conditions, it has been observed that the various types of acute C-spine structural damage do not occur simultaneously, but rather in a sequence, where failure of one component leads to the progressive failure of other components (73,75,77).

Occurrence rate: Various reports have documented the occurrence rate of neck injury among high performance aviators (1,22,35,36,52,69,71). All of these reports used data from pilot surveys except one that was based on safety center reports and questionnaires sent to flight surgeons (71). Based on these surveys, the proportion of high performance aviators that have suffered a flying-related neck injury ranges from 30% during the preceding month (69) and 50.6% during the preceding 3 mo (69), to almost 90% over the course of the pilot's career (1,21,35,52,71).

One large survey (69) found that neck injury is more frequent and more severe in the F-16 than in the F-15, the latter aircraft having a more vertically oriented seat than the F-16. Another survey (13) showed no statistically significant difference in $+G_z$-associated acute neck pain between F-16 and F-15 pilots. However, this second study was limited by small sample size. Other studies (1,22) have found that the total number of flying hours is the only statistically significant factor associated with in-flight neck pain occurrence. One study (1) reported that risk of neck injury increases 6.9% per 100 h of total flying time in the F-16.

Vertebrae and disk injuries: Experiments using compressive axial forces applied to human cadaveric preparations have demonstrated compression, burst, and wedge fractures of the vertebral body in addition to vertebral subluxations, spinous process fractures, facet disruption, and intervertebral disk ruptures (73,76,77,79).

In fighter pilots, compression fractures of the vertebral bodies at the C5, C6, and C7 levels have been documented (2,64). Herniated nucleus pulposus (HNP) has been reported at levels C5-C6 and C6-C7 (24,64). In addition, fracture of the spinous process has been observed at the C7 level (64), although the exact mechanism of this injury was not reported.

Muscle and ligament injuries: Experiments using axial tension applied to human cadaveric preparations have demonstrated intervertebral disk end plate fractures and interspinous ligament disruptions (74,75). Ligament ruptures have also been documented after axial compressive loading of human cadaveric preparations (76). Interspinous ligament injuries have been documented in fighter pilots at the C5-C6 and the C6-C7 levels (2,64). One survey (71) found muscle strain (microtears) to be the most common minor neck injury.

Chronic and Degenerative Processes

Premature cervical spine degeneration results from repeated exposures to high $+G_z$ forces (6,7,19,23,61). After an extensive review, the NATO RTO-TR-4 concluded that repeated, acute injury of soft and hard tissues of the neck leads to spinal disk injuries that initiate degeneration of the spine (6). These reported injuries have occurred in the lower C-spine (i.e., C3-C7). The majority of vertebrae and disk pathology seen in one radiological study of high performance aircraft pilots was at the C4-C5 and C5-C6 levels (29). Recognizing that, in the lower C-spine, these vertebrae have the greatest ROM (60) and the greatest potential for increased load moments and malalignment, the finding is not surprising.

Radiological studies: One study (29) used radiographs taken at a 2-yr interval on the same group of pilots who remained asymptomatic during the interval. No changes, or only minor changes, were seen at the C7-T1 level or below. Statistically significant increases of osteophyte spurring were found at the C5-C6 level. Disk space narrowing was found at significantly increased rates at C4-C5 and C5-C6. This particular finding varied from the typical pattern seen in the general population where disk space narrowing is most commonly seen at a lower level in the cervical spine—C5-C6 and C6-C7. This study also showed that the lower C-spine is the region that is most vulnerable to injury.

It would be expected that the effects on the lower C-spine structures are greatest where there is the greatest ROM and thus, the greatest potential for increased load moments and malalignment. The previously noted increased ROM at C5-C6 and C4-C5 (60) may account for the observed location of the degenerative changes.

A study using cervical MRIs compared three asymptomatic groups: experienced fighter pilots, inexperienced fighter pilots, and age-matched controls without any flying experience (61). The experienced fighter pilots had a statistically significant increase in cervical osteophyte formation, cervical disk protrusion and herniation, and compression of the spinal cord at multiple levels of the C-spine due to both osteophytes and HNPs. Cases of degenerative stenosis of the cervical spinal canal (19) and premature disk degeneration in the cervical spine (23) have also been reported among fighter pilots.

In a cervical MRI study of asymptomatic, experienced centrifuge riders compared with age-matched controls (5), no statistically significant difference was found in the prevalence of spinal disk abnormalities. However, this study was limited by a small sample size and a high degree of between-reader and within-reader variability of MRI interpretations. In addition, centrifuge riders exhibit very little head and neck movement due to the disorienting effect that such movement has in this setting. Thus, their spinal columns would typically be maintained very close to the neutral position, and would, therefore, be at a much lesser risk of acute or chronic injury.

Cumulative trauma: It has been suggested (6,7,10,29,58) that repeated acute soft tissue injury in the C-spine leads to decreased ability for these structures to support the spinal column and predisposes the pilot to more frequent and more severe neck injuries, a rationale similar to the muscular hypothesis for other WMSDs. It was concluded by one study (10) that compromised function of neck muscles may place otherwise healthy individuals at increased risk of spinal injury after physical trauma. It thus appears that, if minor soft tissue injuries could be minimized, more severe injuries and early chronic changes may be reduced.

Prevention Strategies

Using knowledge of the biomechanical characteristics of the neck, the types of forces involved in the high-G flying environment, the intensity and duration of exposure to these forces, and the types, locations, and theoretical mechanisms of acute and chronic neck injuries, it is possible to develop an objective approach to the identification of sound preventive strategies. Potential interventions to reduce or eliminate neck injury in pilots of high performance aircraft can be grouped in terms of primary, secondary, and tertiary prevention.

Primary Prevention

One investigator noted that, “All efforts to reduce muscular strain contribute to preventing acute neck pain among fighter pilots” (20). There are different approaches to achieving this end. Some interventions would focus on aircraft design and personal protective equipment (PPE), while others are directed toward physiological factors in the pilot. Although engineering controls, such as articulated seats that provide head and neck support, would be effective, such will not be available in the near future (19,64). Similar constraints exist for improved PPE, including better helmet design (6,16,19,31). In responding to the situation today and in the coming decade, it is thus important to concentrate on the physiological aspects of prevention.

Pilot candidate screening programs: One approach to reducing C-spine injuries is to screen out pilot candidates with a known predisposition for developing such injuries. Both the Japan Air Self Defense Force (JASDF) and the Royal Netherlands Air Force have such programs based on radiographic examinations (29,35). A major concern is that it has not yet been determined why some fighter pilots are predisposed to developing degenerative changes in the C-spine, even though all fighter pilots undergo similar exposure to high $+G_z$ forces (19). Until the effectiveness of such programs has been conclusively demonstrated, we do not recommend instituting these measures in U.S. military aviation programs.

Preflight warm-ups: Numerous studies have recommended neck stretching as part of a "G warm-up" in the cockpit prior to high-G exposures (1,6,7,13,64,69). One survey of 268 pilots showed a statistically significant beneficial effect of preflight range-of-motion stretching or isometrics (1) but another, more limited, survey of 52 high-performance aviators found no protective benefit. (52).

In-flight techniques: Possible in-flight abatements that have been suggested include minimizing the movement of the head out of the neutral position, using an external support in the cockpit for the head and neck (canopy, seat back, or other support) while under high $+G_z$ forces, pre-positioning the head prior to the onset of $+G_z$, and "unloading" the G forces on the aircraft prior to moving the neck (1,6,7,13,36,53,64,69). One study (1) found a statistically significant decrease in neck injuries in F-16 pilots who placed their head against the seat prior to high $+G_z$ onset, in those who positioned the unsupported head in the desired direction of gaze prior to $+G_z$ onset, and in those who unloaded the $+G_z$ prior to repositioning the head.

Muscle resistance training: Many investigators have recommended resistance training interventions designed specifically for the neck muscles (1,6,7,13,53,64,69,71). Others have recommended whole-body resistance training, either alone or in combination with neck-specific training (1,6,7,13,35,64,69,71). It does not appear, however, that case-control or prospective cohort studies have been accomplished to determine the effectiveness of such interventions among fighter pilots.

One retrospective analysis, using questionnaire data, studied the effects of such interventions on operational F-16 pilots (1). The investigators found a statistically significant decrease in the number of neck injuries in pilots who performed "neck strengthening exercises," but the decrease was not seen among those who performed "body exercises." In spite of the lack of controlled data, some authors have stated that it is reasonable to argue that neck strengthening would confer a benefit (1,6,7,16,17,54,56).

Neck-specific training regimens and techniques: Investigators have noted that the capacity of a muscle to generate force (including the neck musculature) is directly related to its cross-sectional area (45). Therefore, one may postulate that an increase in neck muscle size may stabilize the C-spine and prevent, or reduce, the severity of impairment (11). This supposition supports the thought that dynamic neck and shoulder training may have a preventive effect in fighter pilots (18).

In fact, neck strength training has been suggested to be a key to neck injury prevention in athletes (68). However, the referenced survey of F-16 pilots that showed a positive association of neck strengthening exercises with fewer C-spine injuries reported that only 26.9% of the pilots surveyed routinely did neck strengthening exercises (1).

"Specific" and "intensive" training: "Specific" and "intensive" training regimens may be of particular significance (10,11,51). "Specific" refers to applying the resistance to the exact motion used occupationally, such as the "check six" maneuver, for example. "Intensive" implies multiple sets with multiple repetitions each, against high levels of resistance. In support of this concept, one study found that the greatest gains in strength are observed in activities similar to those used in the training regimen (11). This was true in terms of training mode, joint angle, velocity, movement pattern, and type of muscle action.

Another study involving patients with chronic neck pain (degenerative disk and cervical disk syndrome) showed significant strength increases in C-spine extensors and rotators after 10 wk of "specific" and "intensive" training (51). These patients avoided undergoing previously recommended spinal surgery. Symptoms dissipated as functional status improved in most patients.

The beneficial effects associated with "specific" and "intensive" neck training regimens may be related to how the specific muscles involved in the various neck movements are functionally grouped and employed, as previously described (10,11,38,44,48). The redundancy that exists among these functional groups may be related to the differences in the specific muscles that are activated for a particular neck movement, depending on the degree of force required at the time (10,11). As noted previously, this phenomenon occurs in the recruitment of previously inactive muscles in response to requirements for increased force-generation during neck rotation (10). Such findings suggest that neck muscle training regimens for fighter pilots should use the specific high-risk neck movements listed above, with special emphasis on the "check six" maneuver.

General whole-body vs. neck-specific training: One limited survey indicated that whole-body endurance training was protective for acute in-flight neck pain (21). Another author has suggested that it is possible that the increased amount of weight training done by U.S. Navy pilots while aboard ship may have led to the decreased incidence and severity of neck injuries observed among this group compared with other high-performance aircraft pilots (71). However, another survey of fighter pilots indicated that general muscle resistance training alone was not the definitive answer (52).

A civilian population study (11) found that conventional, whole-body resistance exercises without specific neck exercises did not elicit increases in neck muscle size or neck extension strength. In contrast, neck strength training, in addition to whole-body training, did lead to greater strength, flexibility, and circumference of the neck than whole-body training alone in a group of young, civilian athletes (68).

Although muscle resistance training may be beneficial, many pilots have difficulty accomplishing such training due to a lack of time, experienced trainers, and close-by facilities (1,35,56). Even after establishing the potential effectiveness of such an intervention, the challenge of facilitating long-term adherence to a proven program will remain.

Secondary Prevention

Early diagnosis and intervention: The importance of recognizing and treating the "post-flight sore neck" (sub-clinical or non-acute injury) has been established

(6). The significant concern is that an abnormality of any component of the neck induces additional stresses and strains on the other intact, normal elements of the system (75). Injury is imminent when failure of one component causes increased flexibility or joint laxity, which in turn causes the tolerance threshold of another component to be exceeded (75). In addition, worsening of the original, sub-clinical injury is possible without early intervention (6). Early recognition and treatment of sub-clinical injuries would strongly mitigate such occurrences.

Structured rehabilitation program: The anterior cervical musculature is weaker in patients with cervical sprain/strain or myofascial pain than in normal, healthy populations (65). In addition to passive and pharmaceutical measures included in a treatment regimen, as described below, aggressive rehabilitation of injured muscle is vital (6).

This requirement is supported by investigators who demonstrated that patients with non-spinal cord neck injuries had increases in strength and ROM, and decreases in perceived neck pain, after 8 wk of neck-specific resistance training (4,30). A hand-held dynamometer to measure neck muscle strength may aid in measuring progress and improvement in the treatment of C-spine pain patients (50).

However, considerable levels of resistance are required to rehabilitate neck muscles to their normal functional values (34). Therefore, as in primary prevention, the rehabilitation program should be "specific" and "intensive" (10,51), with particular focus on the high-risk neck movements—especially the "check six" maneuver.

Tertiary Prevention (Treatment Strategies)

Acute injury: Acute, minor, clinical injury has been shown to be a precursor to major injury (6,7,75). It is also theorized that repeated, acute C-spine injury results in premature chronic degenerative changes (6,10,19,23,29,58). Therefore, early recognition and aggressive treatment interventions are important in response to any acute injury (6).

Treatment modalities: Surveys of high-performance aviators have demonstrated that rest, heat and massage, non-steroidal anti-inflammatory agents, and sleep were beneficial for relief of G-associated neck pain (1,6,13).

Structured rehabilitation program: As with the sub-clinical conditions already mentioned, adequate therapy of acute neck injuries demands the inclusion of an early, aggressive rehabilitation program with "specific" and "intensive" training of injured muscle groups, with a focus on the injured groups and on high-risk neck movements.

Conclusions

In this article, we have defined the muscles associated with head and neck movements and those movements associated with an increased risk of neck injury in the high performance flying environment. We have also discussed the intensity and duration of the force exposure in this environment. This occupational exposure can be characterized by the established WMSD risk factors, high force and high repetition. The effects that this exposure has on the neck may be worse when seated in the 30° reclined seat found in the F-16, as compared with the 12–13° reclined seat found in other fighter aircraft.

Considering these concepts in relationship to the types of reported injuries, we have proposed some theoretically sound strategies to reduce neck injury in this occupational setting. These interventions are presented in terms of primary, secondary, and tertiary prevention. The most significant intervention may be "specific" and "intensive" neck muscle training. This type of training would use high levels of resistance and focus on the specific muscles involved, repeating the identified high-risk neck movements in the workout, with special emphasis on the "check six" maneuver.

Recommended Studies

A more extensive study of total hours of flying time ("exposure") and neck injury occurrences ("disease") could provide a statistical description of the exposure-disease relationship with regard to in-flight neck injury. This study should compare aviators of high performance aircraft with aviators of non-high performance aircraft to determine if there is a difference in occupational risk of neck injury between the two groups. The study should also compare F-16 aviators (30° reclined seat) with aviators of other fighter aircraft, such as the new F-22 (12–13° reclined seats). The information gained would serve to clearly define the population at risk and provide a target for preventive intervention. Any identified differences may have increased significance as they are also applied to the seat-back design in future fighter aircraft.

To date, no prospective cohort study has been published that assesses the effectiveness and the aviator acceptance (i.e., whether or not the aviator can and will use them) of the interventions we have described. Such a study should be accomplished, with special emphasis on the benefits and feasibility of a structured neck training program that is based on a "specific" and "intensive" regimen that uses the high-risk movements.

Future Significance

The issues discussed in this article will be of even greater concern in the immediate future with the increased use of helmet-mounted night vision devices and helmet-mounted display systems. These systems will add additional weight to the helmet, and current designs will shift the center of gravity (CG) of the head-helmet further forward of the ear (40). This anterior shift in CG creates larger load moments which require greater supporting forces, even in the neutral neck position. In addition, increased head and neck movement are necessary with these devices in order to compensate for the decreased field of view (night vision devices) and to slew the weapons system for target acquisition and tracking (helmet-mounted displays).

The findings in this article have led to the proposal of some currently untested, but theoretically sound, interventions to reduce neck injuries in aviators of high performance aircraft. Early and ongoing prevention, aggressive treatment and rehabilitation, and future engineering controls are vital to maintaining mission capability and aviator well-being. Prospective analyses of these interventions will provide an objective basis for determining their benefits and the need for any future modifications.

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