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Fast jet aircrew neck pain sources and mitigation strategies literature review

Jordan Bray-Miners
David W.Tack
HumanSystems Incorporated

Prepared by:
HumanSystems Incorporated
111 Farquhar Street
Guelph, ON N1H 3N4
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Technical Authority: Philip S. E. Farrell, Defence Scientist
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FAST JET AIRCREW NECK PAIN SOURCES AND MITIGATION STRATEGIES LITERATURE REVIEW

by:

Jordan Bray-Miners and David W. Tack

Human*Systems*® Incorporated
111 Farquhar Street
Guelph, ON N1H 3N4

HSI® Project Manager: Jordan Bray-Miners
(519) 836-5911

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DRDC Toronto Research Centre
1133 Sheppard Avenue West
Toronto, Ontario M3C 2K9

Project Scientific Authority:

Philip S. E. Farrell
416-635-2000 ext. 2305

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Author

Jordan Bray-Miners
Human*Systems*® Incorporated

Approved by

Philip S. E. Farrell
Scientific Authority

Approved for release by

Name of Document Review Chair
Chair, Document Review and Library Committee

Abstract

High G-induced neck injuries are common in high-performance fighter aircraft. A review of the incidence literature on the association between neck pain and flying high-performance military aircraft highlights that this is a significant problem that crosses nations and aircraft types. A literature review was conducted for Defence Research and Development Canada (DRDC) Toronto Research Center (TRC) as part of the planning process for the future Fast Jet Aircrew Neck- and Back-trouble Mitigating Solutions research project 03eb02. The focus of the literature was on the epidemiology, methods used to model neck pain for fast jet aircrew and the neck pain sources and mitigation strategies. A set of keywords was developed and used to search online databases.

The first component necessary for modeling neck pain sources of fast jet aircrew is understanding the affects of high accelerations on the body. The body behaves differently depending on the direction of the G force however the impact on the body is a combination of the physical force and blood being either drained or forced into different parts of the body. Correlating subjective survey data is the most common method used to model neck pain sources, however addition methods include neck loading data collection with instrumentation such as accelerometers and electromyography sensors, and biomechanical modeling.

Sources and mitigating strategies were organised into operator factors, body-borne equipment, aircrew behaviour, aircraft workspace and organisation factors. Operator factors focused on the relationships between demographic characteristics and neck pain including scoliosis, age, sex, anthropometry, flying history and muscle strength. Body-borne equipment was focused on helmets, and helmet mounted sensor systems and the impact of changing neck supported mass characteristics. Aircrew behaviour sources of neck pain and mitigating strategies related to body postures adopted during flight and the impact they have on neck loading. Aircraft workspace sources include cockpit and seat design as well as the performance capabilities of the aircraft itself. The cockpit and seat design factor into the postures adopted and the performance of the aircraft is linked to the G acceleration levels that can be reached. Organisation sources of neck pain refer to elements of when and why high-performance aircraft pilots fly including factors such as mission durations, mission frequencies, and maneuver frequencies within a mission. Organisation sources of neck pain often relate to muscle fatigue and cumulative effects of high G acceleration exposure.

Résume

Les blessures au cou induites par un taux de G élevé sont courantes dans les avions de combat hautes performances. Une revue de la littérature sur l'incidence sur l'association entre douleur au cou et le vol d'aéronefs militaires à hautes performances montre qu'il s'agit d'un problème majeur qui touche différents pays et types d'aéronefs. Une analyse documentaire a été réalisée pour le Centre de recherches de Toronto (CRT) par Recherche et développement pour la défense Canada (RDDC) dans le cadre du processus de planification du futur projet de recherche 03eb02 s'appellé « Fast Air Neck-and Back-trouble Mitigating Solutions ». La littérature s'est concentrée sur l'épidémiologie, les méthodes utilisées pour modéliser les douleurs au cou chez les membres d'équipage à réaction rapide et les sources de douleurs au cou, et les stratégies d'atténuation. Un ensemble de mots-clés a été développé et utilisé pour rechercher des bases de données en ligne.

Le premier élément nécessaire pour modéliser les sources de douleurs au cou des équipages d'aéronefs à réaction rapide consiste à comprendre les effets des fortes accélérations sur le corps. Le corps se comporte différemment selon la direction de la force G, mais l'impact sur le corps est une combinaison de la force physique et du sang drainé ou forcé dans différentes parties du corps. Les enquêtes subjectives sont les méthodes les plus couramment utilisées pour identifier et éventuellement modéliser les sources de douleur au cou. Cependant, les méthodes supplémentaires incluent la collecte de données sur la charge du cou avec des instruments tels que des accéléromètres et des capteurs électromyographiques, ainsi que la modélisation biomécanique.

Les sources et les stratégies d'atténuation ont été organisées sous la forme de facteurs opérateurs, d'équipements embarqués, de comportement des équipages, d'espace de travail, et des facteurs de l'organisation. Les facteurs opérateurs étaient concentrés sur les relations entre les caractéristiques démographiques et les douleurs au cou, notamment la scoliose, l'âge, le sexe, l'anthropométrie, les antécédents de vol et la force musculaire. Les équipements portés par le corps étaient concentrés sur les casques, les systèmes de capteurs montés sur les casques et l'impact des caractéristiques de masse changeantes soutenues par le cou. Comportement des équipages en cas de douleurs au cou et stratégies d'atténuation liées aux postures corporelles adoptées en vol et à l'impact qu'elles ont sur la charge cervicale. Les sources d'espace de travail de l'avion comprennent la conception du poste de pilotage et des sièges, ainsi que les performances de l'avion lui-même. Les facteurs du poste de pilotage et de la conception des sièges prennent en compte les postures adoptées et la performance de l'avion est liée aux niveaux d'accélération G pouvant être atteints. Les sources organisationnelles de cervicalgie font référence au moment et aux raisons pour lesquels les pilotes d'aéronefs performants volent, y compris à des facteurs tels que la durée des missions, la fréquence des missions, les fréquences de manœuvre au sein d'une mission. Les sources organisationnelles de douleur au cou sont souvent liées à la fatigue musculaire et aux effets cumulatifs d'une exposition à une accélération élevée du G.

Table of Contents

List of Figures

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1. Introduction

High G-induced neck injuries are common in high-performance fighter aircraft. The incidence of neck injuries among military pilots increased dramatically with the advent of jet-powered aircraft. Aviator neck injuries were rare during World War II, but modern higher performance aircraft expose pilots to much higher G forces resulting in higher incidence of neck pain (Shaw, 1948).

A review of the incidence literature on the association between neck pain and flying high-performance military aircraft highlights that this a significant problem that crosses nations and aircraft types. Newman (1997) surveyed 52 fighter pilots from the Royal Australian Air Force. Most pilots (77%) reported experiencing neck injury due to high G_z forces, with 38% experiencing injury levels that interfered with mission completion. Vanderbeek (1988) surveyed 437 U.S. Air Force pilots from three different high-performance fighter jets and found that 50.6% reported experiencing acute neck injury in the preceding 3-month period. The Royal Australian Air Force also investigated the prevalence and operational significance of neck pain in jet fighter aircrew (Smith, 2016). Operationally significant neck pain was reported by 60% of survey respondents over a 12-month period, with averages of 2-4 episodes per year, typically lasting 3-5 days. Almost all pilots (93%) report that their flying performance has been negatively impacted by neck pain.

The introduction of the F-15 aircraft to the Japan Air Self Defense Force in the early 1980's increased musculoskeletal injuries to the neck. Of the 129 pilots surveyed, 89.1% report pain due to flying, with 95% of those from flying the higher performance F-15 jet. According to Knudson et. al. (1988), the introduction of the F/A-18 high performance jet in the U.S. Navy and Marine Corps has evidenced high G-induced neck pain and injury. Most (74%) of the F/A-18 pilots reported neck pain associated with high G-forces. Many (30%) of those pilots required removal from flight status for an average of 3 days.

Pilots exposure to high-G forces alone, particularly when flying air combat maneuvers, fails to provide the full picture for understanding the causal factors and etiology in neck pain and injury. The contributing factors are ubiquitous and multifarious.

A strong association has been established between the extent of exposure to the physical demands of flying and the incidence of pain. Kang (2011) surveyed 1003 male aviators, who flew high-G aircraft, and determined that above a certain level of G the risk of injury does not increase. Kang concluded that the duration and frequency of total G exposure was more influential for neck pain than the level of exposure. Hermes (2010) also reported a strongly significant association between flight hours of exposure and cervical disorder among pilots of high-performance aircraft.

Loads and forces on the head have also been shown to increase the musculo-skeletal demands of flying the structures of the neck. Night vision goggles, used by fighter pilots, are known to increase the risk of neck and shoulder pain further (Äng, 2013). This greater risk is due to the higher helmet weight and anterior shift in the mass of the helmet/head-worn equipment. During air combat maneuvers with NVGs, pilots employ greater neck muscle activation resulting in increased muscle neck strain. Similar concerns were raised regarding helmet-mounted systems for both night vision and display systems (Doczy, 2004).

Head/neck postures during flight and body position also contribute significantly to neck pain, and these postures are often influenced by the workstation design of the cockpit. Verde (2015) surveyed 35 F-16 and 34 age-matched Typhoon pilots on their flight activity and neck pain. Results indicated that the incidence of neck pain in F-16 pilots was much higher (48.6%) than Typhoon pilots (5.7%).

Verde suggested that the difference may be due to the more demanding neck postures imposed by the more reclined seat design of the F-16. Air combat maneuvers and the "check six" position were identified as most causal to injury (Newman, 1997). Smith (2016) also noted that the combination of the "check six" position and wearing a helmet cuing system were considered strong contributors to the incidence of neck pain. Hoek van Dijke (1993) developed a biomechanical neck model to simulate F-16 seated postures and found that the more reclined backrest of the F-16 seat reduced cervical lordosis. Jones (2000) suggested that the more reclined backrest angle of the F-16 may account for the higher incidence of neck injury over aircraft with more upright backrests (i.e. F-14 and F-15). The more reclined backrest angle is thought to encourage more neck flexion during head rotation.

Taking all of these factors together paints a multi-factorial causal model of potential pain and injury-inducing forces on the structures of the neck. An electromyography study of six fast jet aircrew, flying one-on-one air combat sorties with at least four air combat engagements, revealed that extreme neck extension and rotation is very common in air combat and was associated with high levels of muscle activation and fatigue (Green, 2004). Flying high performance aircraft in aerial combat maneuvers results in high levels of neck muscle activation due to high G-forces and mechanically disadvantaged head/neck postures (Netto, 2006). Netto suggests these muscle activation levels are major contributors to the pathomechanics of observed neck injuries in jet fight pilots.

The Aerospace Medical Panel of the Advisory Group for Aerospace Research and Development (AGARD) noted that fighter pilots sustained very high rates of acute injury to the soft tissues of the neck and significantly greater incidences of degeneration of the cervical spine (Burton, 1999). The Panel hypothesized that the acute injuries weakened the soft tissue structures supporting the cervical spine. As this protection weakened the high G-forces of combat flying generated higher loads on the disk structures of the neck, leading to spinal degeneration.

To better understand the causal factors and potential solution space of fighter pilot neck pain a literature review was conducted to support the planning process for the future Fast Air Neck- and Back-trouble Mitigating Solutions research project 03eb02. The focus of this literature review was on the epidemiology, methods used to model neck pain for fast jet aircrew, and the sources and mitigation strategies for fighter pilot neck pain.

2. Methods used to Model Neck Pain Sources

The exact mechanism for acute and chronic neck injuries amongst high-performance aircraft pilots has not been pinpointed in the literature. A range of possible sources, or contributing factors, have been discussed in the literature will be presented in section 3, following the framework reported by Farrell, Shender, and Fusina (2018). The subsections below will focus on reviewing the general impacts of high G forces on the human body, and methods used to quantify the impact of contributing factors including subjective survey responses, neck loading data collection and analysis, and biomechanical neck models.

2.1 Affect of high accelerations on the human body

Voshell (2004) provides a general overview of how G-forces affect the human body. The author starts by reviewing the basics of G-forces explaining that 1 G is the force felt by Earth's gravity and when a body changes speed and direction that force will increase[1]. The authors state that the human body can tolerate a great deal of G-forces however factors that need be considered include where the force is applied on the body, how rapid the onset is, the duration, and the orientation. The earliest manned G tests reported by Voshell were in 1947 by Colonel Stapp who completed multiple high G test runs with varying onset and duration of G-forces (up to 35 G) on a rocket sled. Stapp reported many injures but specific to the level of G-forces, it was reported that above 18 G vision became blurry and eventually white when facing backwards. "Red outs" occurred when facing forwards due to blood being forces against his retinas. Stapp went on to survive a 46.2 G exposure although he suffered a complete "red out" and was nearly unconscious.

Voshell (2004) reports that most knowledge about the physiological effects of G-forces on the human body now comes from studies involving in-flight situations, centrifuges, swings, crash dummies and computer simulations. In general, $+G_z$ forces push your body downward and drains the blood from the head, and the ribs and internal organs are pulled down making breathing difficult. The heart has difficulty pumping blood to the head and eyes, eventually causing vision loss, blackout and unconsciousness. During $-G_z$ forces blood is pushed into the head, slowing the heart down and causing "red outs". $\pm G_x$ acceleration tolerances are higher than G_z but cause respiration and lung inflation movement issues creating breathing difficulties. The largest concern with G_y accelerations is with respect to supporting muscles including the head and neck (Voshell, 2004).

Shiri, Frilander, Sainio, Karvala, Sovelius, Vehmas, and Viikari-Juntura (2014) conducted systematic review and meta-analysis to relate high performance aircraft type and flight hours with cervical and lumbar pain and radiological degeneration. They found no relationship between exposure to G-forces and cervical disk degeneration, however exposure to higher G-forces was related to neck pain in high performance aircraft pilots. The authors did not report a magnitude that constituted as high but an earlier report by Coakwell, Bloswick, & Moser, Jr., (2004) state that forces above 4 G_z have been linked with potential neck injury and most surveys report symptoms in the 4-9 G_z range. Sarsfield, O'Hara, and Wright (2012) review the literature and also report that repeated loads of 4 G is the minimal threshold causing injury and the average G level for acute injuries was 6.7 G.

[1] In other words, when a body changes speed and direction (i.e. accelerates), this force due to acceleration plus the force due to gravity act on the body equals the resultant force. The resultant force vector (or acceleration vector) may be expressed as a multiple of G-force (or G).

There are other factors specific to high performance aircraft pilots that have been reported to contribute to neck pain beyond just the fact that the aircraft is exposed to high G acceleration. These additional factors, or mechanisms, will be discussed in detail in section 3. The following subsections will outline some of the methods that have been used to assess the contributing factors including subjective survey responses, neck loading measurement and calculations, and biomechanical neck models.

2.2 Subjective Survey Responses

One of the most common data collection methods for determining the prevalence of neck pain amongst high performance aircraft pilots and possible causal factors has been the administration of subjective surveys. Due to the high volume of literature in this area the studies review in the following section were down selected to only include ones that have extended their survey response analysis to determine correlations between dependent and independent variables. The common survey administration and analysis methods of each study will be highlighted along with their key findings and points of criticism.

A group of authors aimed to correlate individual, work-related, and flight-related characteristics of high-performance aircraft pilots with self-reported one year prevalence of neck pain (De Loose, Van den Oord, Burnotte, Van Tiggelen, Stevens, Cagnie, Witvrouw, & Danneels, 2008). The authors surveyed 90 F-16 pilots from The Belgian Air Force and The Royal Netherlands Air Force with a questionnaire divided into three parts: i) general, ii) work-related, and iii) pilot specific. Survey responses were divided into two main groups, neck pain group and healthy group. The neck pain group reported greater than two pain episodes lasting a least one day within the past 12 months (N=17). The neck pain group did not report more flight hours or flight hours with NVGs than the healthy group and there were not differences found between individual factors like age and body mass index (BMI). There were no significant differences found in leisure activities between the two groups, and the authors also did not find a difference in the reported preventative strategies pre-flight, during flight or post-flight. Based on the survey responses the authors state the for the neck pain group complaints most likely occur without NVGs when a G level exceeds 4 G. Furthermore, the neck pain group reported that the "check-six" maneuver and general neck rotation induced the complaints. The only work-related differences found were that the neck pain group reported more hours of computer work per day, they had more reports of being mentally tired at the end of the day and that they were annoyed by others at their job. The authors discuss that many of their findings differed from other studies found in the literature and they pointed to two main compounding factors: one that their study relied on the participant's memory of what occurred within the last year, and two that they had a low number of participants in the neck pain group (N=17).

Another group of authors that looked to identify high performance aircraft pilot behaviors associated with neck pain using self-reported survey responses were Tucker, Netto, Hampson, Oppermann, and Aisbett (2012). The authors surveyed 82 Royal Australian Air Force fighter pilots using 18 questions. The questions were grouped in six sections: i) personal details and flying experience; ii) helmets and night vision goggles/helmet-mounted display system usage; iii) preventative activities while flying to minimize the risk of neck pain and injury; iv) neck strain, pain or injury sustained; v) neck pain management; and vi) neck pain prevention while flying. Only sections one, three, four and six were reported on by Tucker et al. (2012). The dependent variables that the authors were trying to predict from pilot behaviours were: number of neck pain episodes during flight, number of neck pain episodes after flight, duration of worst episode, duration of average episode, and longest duration of being deemed temporarily medically unfit for flying (TMUFF). They found that the only predictor for neck pain episodes during flight was flight hours. Neck pain episodes after flight was predicted by flight hours, frequency of neck exercise between flights, and sum of preventative actions performed during flight. Duration of their worst pain episode was predicted by flight hours and weekly desktop work hours. Duration of their average pain episode was predicted by flight hours and the use of preventative actions during flight. The dependent variable with the most predictor variables was longest duration of TMUFF, which was predicted by age, height, frequency of neck and resistance exercises, sum of preventative actions during flight, and amount of desktop work hours. The authors conclude that neck pain in fighter pilots can be predicted from behaviours and preventative strategies could be put in place to consider the risk factors such as flight hours, age, desktop work hours, and frequency of exercise.

In self-reported survey study by Kang, Hwang, Lee, Tang, and Park (2011) more attention was brought to the cumulative effects of G force on neck pain. They reported on surveys completed by 1085 active pilots from the Republic of Korea Air Force. The depend factors in this study were whether the aviator had experienced neck pain, the frequency of the neck pain, and severity of the neck pain. The authors found the following three significant correlations:

i) The monthly duration of G_{max} exposure, flight hours, and BMI were significantly related to the experience of neck pain;

ii) The frequency and monthly duration of G_{max} exposure were both significantly related to the frequency of neck pain.

iii) The monthly duration of G_{max} exposure and seat type were significantly related to the severity of neck pain.

The authors discuss that the significant effect of frequency and duration of G_{max} exposure on the dependent variables, along with the fact that G_{max} level was not a significant factor indicates that G level could have a ceiling effect. When G_{max} is above the ceiling level the amount of exposure becomes more influential on neck pain (Kang et al., 2011). This is an important finding because it highlights the importance of the cumulative effects of high G exposure, and studies looking at mitigating strategies for fast jet pilot neck pain would benefit from a detailed and integrated Mission Function Task Analysis (MFTA) and Physical Demands Analysis (PDA) similar to Tack, Bray-Miners, Nakaza, Osborne, & Mangan (2014).

Subjective surveys are effective at determining the independent variables that are correlated with neck pain amongst high performance aircraft pilots, however they are not effective at explaining why the correlations exist. A detailed MFTA and PDA allows for a quantitative analysis to be conducted including the determination of external neck loading and muscle activation levels for individual postures and tasks, and cumulatively throughout a mission. This type of quantitative analysis can be used to further investigate why different independent variables are correlated with neck pain and better develop future mitigating strategies.

2.3 Neck Loading Data Collection and Analysis

Different tools and techniques used to quantify the loads acting on the neck during high performance aircraft flying have been reviewed from the literature. Examples of the range of techniques will be provided in the following paragraphs including force and moment calculations based on acceleration profiles, either from a helmet mounted sensor or from aircraft G profiles, and muscle activation levels based on EMG data. There was also a range of data collection environments such as lab tests implemented pre and post centrifuge tests, flight simulators, as well as data collection during actual flight. The common data collection and analysis methods of each study will be highlighted along with their key findings and points of criticism. Details of the calculation models that were reviewed will be discussed in section 2.4.

Coakwell, Bloswick, & Moser, Jr., (2004) provide an overview of the biomechanics necessary to calculate neck loading during high performance flying. They state that compressive, tensile, and shear forces act on the C-spine due to both acceleration and vibration. A standard axes system includes $+G_x$ acting anterior to posterior, $+G_y$ acting laterally from left to right, and $+G_z$ acting superior to inferior. In reference to how forces in each direction generally affect pilots: G_x forces may result in flexion/extension bending moments, G_y forces may result in lateral bending moments and G_z forces may result in compression forces on the spine. The authors also discuss how shear forces occur simultaneously in multiple axis as the aircraft accelerates and injuries to neck structures may be caused by excessive shear forces alone.

Coakwell et al. (2004) provide a summary load calculation and state that static load equivalents of 471-638 N can be generated at +9 Gz acceleration, which is achieved during high performance flying. For prospective, the authors state that the gravitational force of a 3.5-5 kg head is approximately 34-49 N. The authors reviewed three other studies that measured in-flight forces and muscle activity to calculate neck loading. The first study calculate C-spine joint reaction forces based on helmet-mounted accelerometer data captured during F-16 flights. Their calculated muscle forces approached the maximum value of 150 N for their muscles of interest, which was taken from cadaver experiments. They also found compressive forces exceeded those that caused fractures during cadaver experiments. The two other studies both recorded muscle activity using electromyograms (EMGs) and compared muscle activity during Hawk MK 51 flight to maximum voluntary contractions (MVCs). The first study reported a mean peak "lateral neck muscle" force of 84.8% MVC. The max peak value measured was 257% MVC, which caused an acute neck injury. The second study reported by Coakwell et al. (2004) that looked at EMG had more proscribed flight conditions and head postures. They reported that with the neck rotated and the aircraft under +4 G_z acceleration the mean peak "cervical erector spinae muscles" force was 79.5% MVC, with a max peak value of 189.7% MVC. Their second proscribed scenario was with the neck moving from flexion to extension under +4 G_z acceleration, where they reported a mean peak muscle force of 55.8% MVC and a max peak value of 109.9% MVC.

Netto and Brunett (2006) collected EMG data from six pilots flying Lead-In Fighter Hawk 127 under a combination of three different $+G_z$ accelerations (1, 3 and 5) and four head postures (neutral, turn, extension, and check 6). EMG data was collected using surface electrodes recorded by a data logger placed in the pilot's flight suit and muscle activity was reported as a percentage of maximum voluntary isometric contractions (MVICs). Three-dimensional (3D) neck joint angles were calculated post flight by simulating the motions recorded by the in-flight video using an electromagnetic tracking device. The authors report an average muscle activation for three acceleration levels were 16%, 24% and 33% MVIC for 1, 3 and 5 $+G_z$ respectively. They also reported that turn, extension and check 6 head postures all resulted in significantly higher average muscle activation than the neutral posture. Furthermore, check 6 had significantly higher muscle activation than both turn and extension. The highest average muscle activation was reported as 71.5% MVIC and occurred in the left sternocleidomastoid muscle during the check-6 head posture under +5 G_z acceleration. The studies range of motion (ROM) results were reported as a percentage of their max ROM from neutral which were found to be: 63.4 ± 4° extension, 70.6 ± 5° rotation, and 52.1 ± 9° lateral bending. Overall the head postures were reported to have the following ROM in their primary movement plane: rotation – 67 % axial rotation, extension – 73% neck extension, and check-6 – 87% axial rotation. The authors conclude that their study results represent relatively high levels of both neck muscle activation and head postures near their end-range of motion which are factors in neck injuries. They also suggest musculoskeletal modeling and studies looking at the benefits of neck strengthening strategies to further understand the cause of neck injury among high performance aircraft pilots (Netto & Burnett, 2006).

Äng and Kristoffersson (2013) collected surface EMG data from pilots during standardized 2.5 hr duration dynamic flight simulator trials. Their aim was to evaluate the effect of night vision googles (NVGs) on neck muscle activity. The simulated flights included 1 hour at 1 G_z followed by 1.5 hours dynamic flight with a G_z profile ranging between 3 and 7 G_z. Five senior fast-jet pilots on active duty from the Swedish Air Force participated in the study. The dynamic flight simulator is based on JAS 39 Gripen aircraft, which is what the pilots were familiar flying, and included real aircraft hardware. The flight simulation visuals were presented using three 20" monitors located in front of the pilots. EMG data were recorded from the sternocleidomastoid, splenius capitis, erector spine C7-T1, and upper trapezius. Root mean square values for EMG signals were calculated and results reported as percentage of pre-flight maximal contraction.

The results report by Äng and Kirstoffersson (2013) do not strongly support their hypothesis that neck muscle activity would be higher while wearing NVG equipment. The only reported significant effect of the NVG equipment was found during the 3-5 G_z portion of the dynamic simulation. The authors discuss two factors that may be affecting the lack of statistical significance during the portions of the dynamic simulation that increased up to 7 G_z: their small sample size, and their instruction that participants avoid large head movements under G.

Äng and Kristoffersson (2013) did report significant main effects of muscles, such that the erector spine was more active than other muscles. They also reported a main effect of G level with 7 G_z (20% MVC) resulted in greater overall muscle activity than 5 G_z, 3 G_z, and the 3-5 G_z portion of the dynamic simulation, 10%, 9% and 6% MVC respectively. The highest muscle activity was reported in the final 7 G_z episode at the erector spine and was shown to be 37% MVC. The other three muscle sites ranged from 10% to 20% MVC.

Eveland, Esken, Shouse, Goodyear, and Kane (2008) combined MVC strength, EMG muscle activity level and task performance data collection pre and post multiple centrifuge trials to investigate changes in muscle fatigue when helmet mass properties are changed. EMG data were collected using surface electrodes at the neck and upper shoulders. The two chosen tasks were a target recognition task and target acquisition task and the performance of the tasks was expected to be correlated with muscle fatigue. Variable weight helmets were used to represent a basic flight helmet (3.0 lb), and two heavier helmet conditions, one based on the Joint Helmet Mounted Cueing System (JHMCS) (4.5 lb), and the second based on JHMCS variant with panoramic night vision goggles (PNVG) (6.0 lb). The authors selected their 11 participants (8 male, 4 female) from a pool of active duty Air Force members that had completed medical evaluations and training to exposures to high G accelerations. Additionally, the participants completed training specifically for the study, which included training in the centrifuge with gradually increased helmet weight and G level, and training on the two simulation tasks. On test days the participants completed two 90-minute dynamic high G trails, with a G profile based on actual flight data. The mission scenario included a G warm-up representing a "G checkout", low G traveling to a mission site, high G engaging the target, and low G returning from the mission. The max G level was set to 7.5 G_z. The two mission scenarios were preceded and followed up with a series of MVC and endurance time strength testing, static target recognition, and target acquisition. Participants completed the test protocol over three six-hour test days, one for each helmet condition. Their study design and analysis were aimed at determining if there was an overall effect of helmet condition and interaction between helmet condition and test segments signifying a difference in performance over time.

Eveland et al. (2008) reported significant declines in MVC strength, endurance time, and time to acquire targets. The authors conclude that these results are due to muscle fatigue. However, each helmet condition showed similar trends throughout the test procedure and therefore the authors did not find significant interactions between helmet condition and test segment. This result signifies that there was no significant effect of helmet condition on muscle fatigue, even though there were trends in the data and subjective survey responses results that showed differences between helmet conditions. The authors discuss that a contributing factor to the lack of statistically significant results may be their study design. The authors chose to have all participants complete the testing with the heaviest helmet on the last test day to avoid losing participants due to injury, and therefore a training effect may be present.

Collected data during live flight or in a centrifuge may not be an option for all researchers due to the resource requirements (expenses, air worthiness, labour requirements, ethical and safety boundaries, etc.). An alternative to collecting neck loading data directly is the use of a biomechanical model and some examples will be discussed in the following section.

2.4 Biomechanical Neck Models

There are several different biomechanical neck models that can be found in the literature. They have different levels of fidelity and corresponding applications and therefore the following paragraphs will focus on models that have been applied to high performance aircraft pilots. Details of the models, applications and points of criticism will be provided.

A group of authors completed a literature review and summarized the relevant biomechanics of the neck into five sections: functional roles of neck structures, normal C-spine movement, C-spine models, tolerance limits of neck structures, and variation of C-spine posture from neutral (Coakwell, Bloswick, & Moser, Jr., 2004). They list the hard tissue structures as vertebrae and intervertebral disks, and the soft tissue structures as ligaments and muscles. The functional role of the hard tissue structures is to be load-bearing and resist compressive forces. The functional role of the soft tissue structures is to stabilize and support the hard tissue structures, primarily by resisting tensile forces. The ligaments and muscles also function to provide movement.

Coakwell et al. (2004) define three groups of vertebrae that combined with the sacrum and coccyx provide axial support. The cervical spine (C1-C7), the thoracic spine (T1-T12) and the lumbar spine (L1-L5) are the three groups of vertebrae separated by intervertebral disks. These disks are a combination of the nucleus pulposus, two cartilaginous plates and the annulus fibrosus.

With respect to the soft tissue structures Coakwell et al. (2004) describe a complex system of ligaments and muscles located along the length of the spine. The ligaments act to support and stabilize the spine while the muscles provide the motion. An example of the complexity is that they state there are over 40 muscles attached to the cervical spine and they do not act along straight lines but have multiple lines of action. The authors discuss that the splenius capitis, semispinalis capitis, semispinalis cervicis, and multifidus muscles are the major muscles responsible for neck extension. The major contributors to neck flexion are the bilateral components of the sternocleidomastoid muscle. With respect to lateral bending the ipsilateral component of the sternocleidomastoid is the primary muscle contributor. The authors state that axial rotation has the most contributing muscles including ipsilateral splenius capitis, levator scapulae, scalenus, and the contralateral sternocleidomastoid.

Coakwell et al. (2004) review two C-spine models, a sagittal plane model and a kinematic model. They state that sagittal plane model has been applied to determine the maximum load that can be supported by the neck at different flexion/extension angles. The model is based on an equilibrium force at each intervertebral joint, which is a balance of four component forces: i) the external load, ii) the reaction force of the joint acting at the center of the reaction, iii) the muscle tension acting about the center of the reaction, and iv) the ligament tension acting about the center of reaction.

The kinematic model reviewed by Coakwell et al. (2004) was original presented by Snijders, Hoek van Dijke, and Roosch (1991). It too was a cervical spine model that was developed to better understand the how joint reaction forces change through a range of static head postures. Their research area of interest was vertebrae failure during F-16 flight. They define a kinematic model that simplifies the eight link chain between the head and C7 vertebrae in three major ways: i) axes of rotation are all located in the middle of the joints, ii) C3-C7 are defined as a single link with a variable length depending on the inclination of the link, and iii) flexion/extension only occurs at the atlanto occipital-C1, C1-C2, C2-C3 and C7-T1 joints. The origin of their model is at the C7-T1 joint and seven additional model points are identified and consist of a combination of muscle attachment points, joint centers and center of mass location. The authors defined the relationships between these points based on the literature and estimates from X-ray photographs. They also define a set of algorithms that can be used to define the behavior of the points at different static postures. The authors went on to include 13 muscles in their model with defined attachment points and lines of action. A set of equilibrium equations were defined for different segments of the model and an optimization procedure was completed using the weight of the head, acceleration forces and weight of a helmet as input parameters to determine the muscle forces and joint reaction forces. The authors were able to calculate muscle forces and joint reaction forces as functions of flexion/extension and axial rotation angles. They concluded that the results from their model were relatively similar to other muscle forces in the literature but did point out that their model is very sensitive to geometric data taken from the literature.

Coakwell et al. (2004) discuss how neither of the two models they reviewed describe the actual forces that would be acting on the C-spine during high performance flight, but it would be possible to calculate them. Another useful application of the models is how they support other studies that show a decrease in tolerance limits when head position deviates from neutral. The principal explanation for this finding is that the moment arm of forces acting on the neck increases as the neck moves away from neutral causing an increase in the muscle forces required to counteract the neck moment and support the head.

The next aspect of Coakwell et al.'s (2004) biomechanical review relevant to the back and neck included the tolerance limits of neck structures. They reviewed studies that included both cadaver specimens and human subjects. They reported the following limits:

- maximum compression loads of the vertebrae ranged from 2 to 7 kN;
- maximum compression of intervertebral discs was over 400 kg;
- maximum tension of the anterior longitudinal ligament was 120.58 N at a load rate of 8.89 mm/s and 349.48 N at a load rate of 2500 m/s;
- maximum tension load of the ligamentum flavum was 130.64 N at a load rate of 8.89 mm/s and 335.07 N at a load rate of 2500 m/s;
- maximum extensor muscle moments, at 15-60° extension, of 65.1 N·m for males and 53.4 N·m for females;
- maximum flexor muscle moments, at 45° flexion, of 36.5 N·m for males and 32.4 N·m for females;
- the whole neck has a max acceleration load of +30 G_z when the head is neutral, +24 G_z when the head is flexed 25°, and +15 G_z when the head is extended 25°.

Shender and Paskoff (2005) presented an anatomically based parameterized probabilistic spinal injury prediction model to be applied in the determination of injury risk. The model accounts for sex, size and loading factors and was developed specifically for fixed and rotary wing aircrew being exposed to high G accelerations, repeated shock, impact, ejection, and crashes. Their approach included the following five steps: i) define the characteristics of the cervical spine; ii) develop their prediction model; iii) define the injury risk based on small females; iv) determine the effects of head support mass characteristics on injury risk; and v) develop technologies to mitigate injury.

Shender and Paskoff (2005) defined the mechanical properties of the cervical spine using: quantitative computer tomography to provide geometric and bone mineral density data; cryomicrotomy to provide soft tissue geometry and attachment points; and measuring the sub-failure material properties of the cervical column, motion segments, and failure characteristics of C6 and C7 under multiple different loading conditions.

Shender and Paskoff (2005) then used the mechanical properties along to define probability distributions related to exceeding injury tolerance levels. The distributions take into account loads, material properties, and geometries that take into account anthropometry and sex. A finite element mesh model sample image representing a 106-120 lb female is seen in Figure 1.

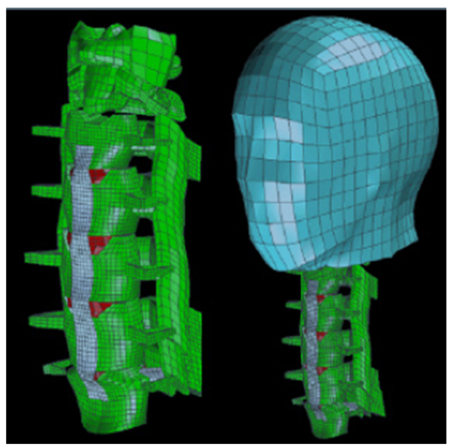

Figure 1: Sample finite element mesh model from Shender and Paskoff (2005).

Zhou, Whitley, and Przekwas (2014) present a dynamic whole-body musculoskeletal fatigue model that was developed specifically to show the loading and fatigue of high-performance aircraft pilots. The authors suggest that seat incline and hand placement play a relevant role in the musculoskeletal loading calculations and therefore a whole-body model is necessary. They define all the main body joint centers and rotational degrees of freedom as well as an eight joint, 24 degree of freedom neck musculoskeletal model. An image of all joint axes and neck muscles can be seen in Figure 2.

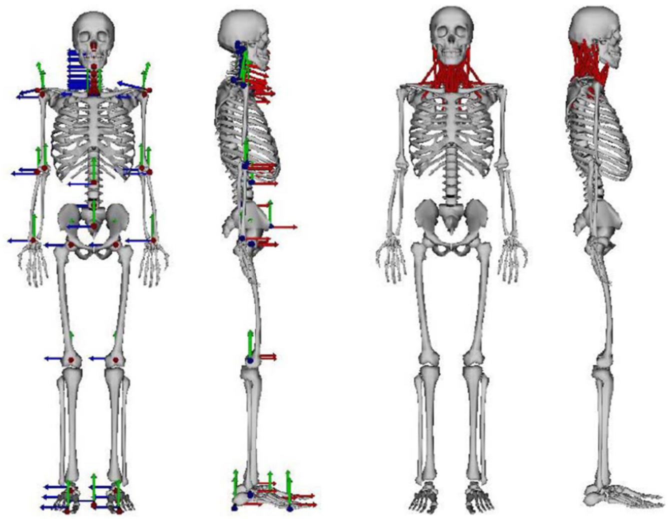

Figure 2: Zhou et al. (2014) whole-body musculoskeletal joint axes and neck muscles

Zhou et al. (2014) describe a reduced coordinate dynamic simulation approach that implemented Lie algebra formulation for multibody dynamics. Their control framework for the dynamic simulation used a reference motion in joint space as the input, and desired joint accelerations are calculated from the difference between the target motion states and current position and velocity states. Inverse or hybrid dynamics are used to calculate joint torques were then calculated based on the desired joint accelerations and known external forces. In the final step of the control model, forward or hybrid dynamics are used to predict position and velocity states of all joints. Focusing on the neck joints, muscle forces were determined by minimizing an objective function that finds the most appropriate muscle force combination to generate the desired joint torques. To account for a reduction in muscle capacity due to fatigue the authors developed a new fatigue model based on a three-compartment muscle model presented in the literature (Xia & Frey Law, 2008). The fatigue model is integrated as part of the control process during forward or hybrid dynamics calculation step to ensure that the muscle forces being calculated represent the current muscle capacity due to fatigue.

Zhou et al. (2014) used their developed musculoskeletal model to analyse neck loading of a normal "look-ahead" posture compared to the check-6 posture. Body postures, and head and helmet mass properties were taken from the literature. Figure 3 shows two images from Zhou et al. with their whole-body model in the look-ahead and check-6 postures.

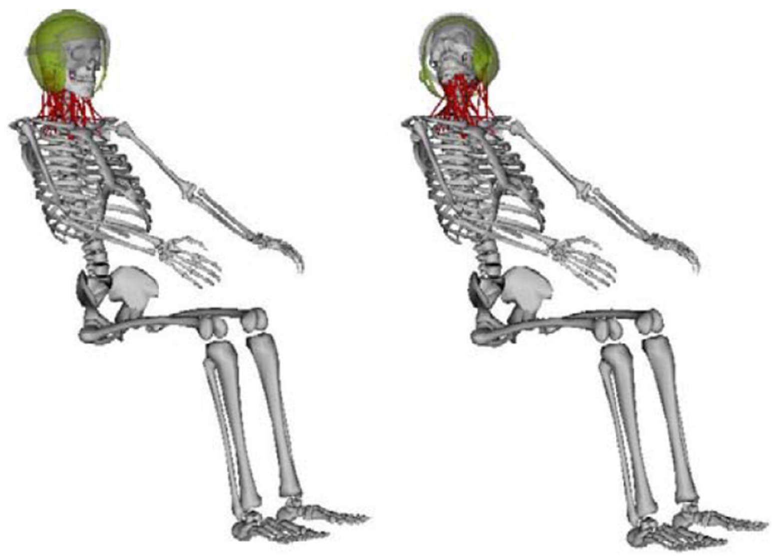

Figure 3: Zhou et al. (2014) look-ahead and check-6 body postures

The authors applied a G_z time domain profile also taken from the literature and were able to show the neck flexion-extension, axial rotation, and lateral bending moments over time. An example of the flexion-extension moment profile from Zhou et al. (2014) is shown in Figure 4.

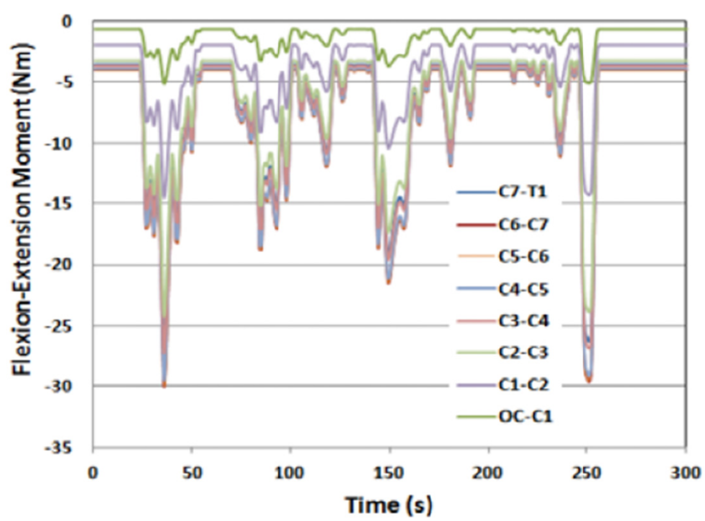

Figure 4: Sample data output from Zhou et al. (2014)

Zhou et al. (2014) discuss that the balance moment required to counteract the calculate joint moments are a combination of passive joint resistance and active muscle moments. Therefore, they calculate passive joint stiffness at each cervical joint and then determined the additional muscle moment, and subsequent muscle force, needed to generate the remainder of the balance moment. Figure 5 shows a sample image of individual muscle activation and fatigue at a peak G_z event during the simulation.

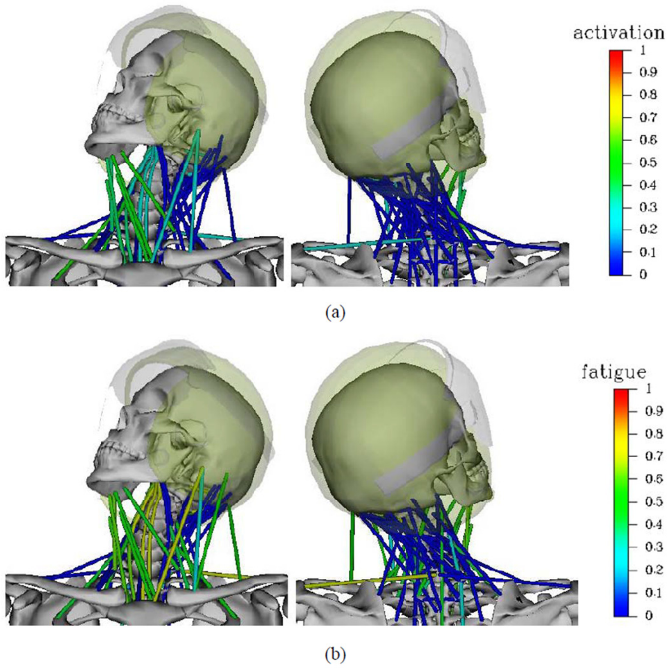

Figure 5: Sample muscle activation and fatigue levels from Zhou et al. (2014)

Zhou at el. (2014) also highlighted their ability to solve compressive joint reaction forces that are a combination of acceleration forces and muscle forces. A sample of the simulation compressive joint reaction forces for the check-6 posture are shown in Figure 5.

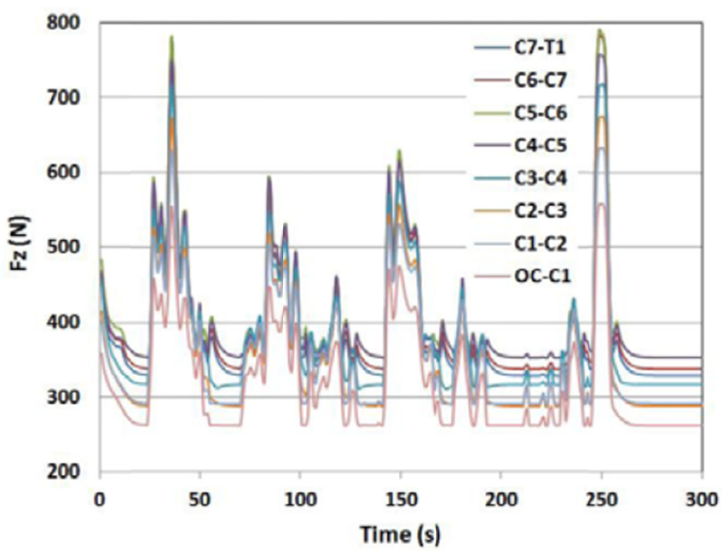

Figure 6: Sample compressive joint reaction forces from Zhou et al. (2014).

Zhou et al. (2014) conclude that their presented model can be used to predict neck musculoskeletal loads and neck muscle fatigue for high performance aircraft pilots. Furthermore, the authors state that there developed methods can be used for: injury prediction, injury mechanism investigation, and helmet design.

Different levels of detail and fidelity related to biomechanical models can be found in the literature. When developing a model or deciding on one to reference it is important to understand the research question at hand and limitations of the model.

The methods used to model neck pain sources that have been reviewed in section 2 were in most cases applied to define the critical sources of neck pain and discuss mitigating solutions. Those aspects of the literature will be reviewed in section 3.

3. High Performance Aircraft Pilot Neck Pain Sources and Mitigation Strategies

A range of neck pain sources, or contributing factors, have been discussed in the literature and will be presented in the following subsection. The sources have been organized based on the proposed framework for factors that impact aircrew neck pain reported in Farrell, Shender, and Fusina (2018).

3.1 Operator Factors

Operator factors (referred to as Human factors in Farrell et al., 2018) that may be sources of neck pain refers to who the aircrew are. The relevant demographic information can include, but is not limited to: age, sex, anthropometry, flying history, muscle strength and other personal characteristics.

Personal characteristics such as age, flying experience and flight hours are naturally related and challenging to isolate. Placentino (2016) found no relationship between self-reported prevalence of neck pain and age, experience, or total flight hours among Typhoon aircraft pilots but a significant, moderate correlation was found among F-16 pilot for flight hours, although the F-16 generally tended to be older, more experienced pilots. Placentino's findings are indicative of the challenge researchers face isolating age and flying experience.

When comparing age and flying experience amongst pilots one author (Hermes, 2010) reported that accumulated flight hours was a stronger predictor of spinal disorders than age alone. One group of authors that took it one step further to isolate age and flying experience (Petren-Mallmin & Linder, 1999) compared cervical spine MRIs of experienced high performance aircraft pilots (mean age 42, mean accumulated flying time of 2,600 hours) to age-matched controls without flying experience and found that pilots evidenced more degenerative neck damage than controls (i.e. significant increase in cervical osteophyte formation, disk protrusion and herniation, and spinal cord compression).

In reference to sex, studies show that females evidence higher reports of neck pain than males in the general population (Cote, 2004, Croft, 2001) however there were no studies relating the incidence of neck pain in high performance aircraft to sex. The higher risk in females may stem from weaker neck muscles than males, relative to helmet weights, but population data may not generalize well to a specialized sub-set like female pilots. An investigation into neck injury criteria following pilot ejection during helmet wear did not find a significant sex difference for peak neck injury criteria (Parr, 2013). As well, a study of neck strength, endurance, and discomfort wearing a range of helmet weights (3-6 lbs) and centers of mass (normal and forward of normal to represent an HMD) did show that males were stronger and had longer endurance times for neck exertions than females but no differences were found in neck discomfort or fatigue (Gallagher, 2008).

Physical characteristics such a neck muscle strength and range of motion have been the subject of many studies related to neck pain of fast jet pilots including De Loose et al. (2009) who completed a study with 90 F-16 pilots from both the Belgian Air Force and Royal Netherlands Air Force. Their data collection included a subjective survey, along with neck strength, neck position sense and neck range of motion quantitative measurements. The authors' aim was to determine if there were differences in the quantitative measurements between pilots who reported neck pain and those that did not report neck pain. No significant differences were observed between the two groups of pilots with respect to maximum isometric neck muscle strength, neck position sense in both the sagittal or horizontal plane, and active cervical range of motion in the frontal plane. The authors did report the neck pain group having lower cervical range of motion in the sagittal and transvers planes. De Loose et al. (2009) do not discuss a known reason for the reduction in cervical range of motion however they suggest that flying high performance aircraft may cause shortened neck musculature or degenerative changes. One limitation of the present study is that of the 90 pilots included, only 17 were placed in the neck pain group.

One report that contradicts the findings of De Loose et al. (2009) was Sarsfield, O'Hara, and Wright (2012). Sarsfield et al. review studies that report a reduction in risk of neck injury for pilots who perform neck strengthening exercises, suggesting that neck strength is potential factor contributing to neck pain.

Neck flexibility and strength exercises have been proposed as a mitigating solution to reduce neck pain. However there is been mixed results in studies that aimed to show a statistically significant benefit (Burton et al., 1999; Coakwell, Bloswick, & Moser, Jr., 2004). Coakwell et al. (2004) discuss several mitigating solutions specific to the neck strength and range of motion, including: preflight warm-ups, muscle resistance training, neck-specific training regimens and techniques, and specific and intensive training. In most cases they reference both studies that have shown benefits and those that have not, and they suggest that this question has lacked sufficient case-controlled studies to meaningfully answer the question.

The positive benefits are reinforced by the findings of Albano (1998) who reported that neck strengthening and stretching exercises prior to flight reduced the incidence of neck injuries, although neck exercises were also combined with in-flight head positioning techniques to help brace the neck in high-G maneuvers. In contrast, Alricsson (2004) reported that pilots of high-performance aircraft, performing a supervised neck strengthening program for 6-8 months (aka reinforced group), significantly increased their neck strength and endurance over a reference group of pilots (aka non-reinforced group). However, there were no significant differences in the resulting reports of neck complaints between the two groups. It is difficult to draw meaningful conclusions here because the reference group would likely still have performed an exercise program, they just weren't supervised and encouraged like the test group. The authors suggested that customized, individual training programs may yield a better result.

Jones (2000) did not find any relationship between pre-flight stretching and a reduction in neck pain episodes, however they did find that a regular weight training program among F/A-18 pilots approached a significant reduction in neck pain episodes. A similar effect was not observed amongst F-16 pilots. The research was based on a survey of military fighter pilots (i.e. T-38, F-14, F-15, F-16, and F/A-18 aircraft).

Studies have also tried to determine the benefits of neck-specific training vs whole-body training. Hamalainen (1998) compared the effects of two neck training methods on lost workdays: dynamic vs helmet-borne weights. Dynamic training included active physiotherapy with warm-ups, stretching, and dynamic neck and shoulder training while the helmet-borne weight training involved moving the head and neck through the complete range of motion while wearing their helmet plus 10-20% MVC of additional weight. Both groups evidenced similar improvements in neck strength, but the dynamic training group had fewer lost days than the helmet-borne training group. Due to the small sample size and the lack of a control group, the authors were not able to draw any firm conclusions.

Investigations of neck pain in the general population indicate that previous neck injury is a significant risk factor in predicting future neck injury (Croft et al., 2001). There is some evidence that repeated acute soft tissue injuries can weaken the neck and predispose a pilot to more frequent and more severe injury (Coakwell, 2004). Burton et al. (1999) suggested that pilots should be made aware of the increased risk of spinal injury when flying with sore necks. Furthermore, the author stated that pilots should be encouraged to adopt a healthy lifestyle of diet and posture.

Coakwell et al. (2004) suggest that pilot candidate screening programs could focus on identifying fighter pilots who are predisposed to developing neck injuries. Screening programs based on radiographic imaging are already being implemented by a couple nations, but the authors are not able to report on their success.

3.1.1 Scoliosis

Biomechanical aspects of spinal curvature can predispose a pilot to a higher risk of low back injury during high G exposures (American Society of Aerospace Medicine Specialists, 2008). Griffin (1975) noted that the incidence of spinal fractures increased dramatically when pilot posture was misaligned (from 38% to 69%). He suggested that the incidence of spinal fractures during ejection increased when a pilot had to bend forward and pull the ejection handles versus sitting upright and ejecting. Griffin concluded that spinal posture and alignment at the time of ejection are important in injury incidence. The presumption adopted for aeromedical standards was that this association of misaligned spinal postures to such accident data can be generalized to spinal curvature abnormalities with regard to pilot safety in ejection seat aircraft. Scoliosis, an abnormal lateral curvature of the spine, is thought to exaggerate both static and dynamic loads on the spine which, when involving extremely high forces such as aircraft ejection, can greatly increase the risk of severe injury (Malik, 2001).

Based on such research, nations have adopted screening guidelines for pilots with reference to spinal curvature abnormalities. Example guidelines for scoliosis include:

> Canadian Air Force: disqualified for ejection-seat-equipped aircraft if scoliosis is >20 degrees. (CFEME, 2012)
>
> U.S. Navy: disqualified if scoliosis >20 degrees, as measured by the Cobb method, but can be waived up to 30 degrees on a case-by-case basis. (ASAMS, 2008 and U.S. Navy Aeromedical Waiver Guide, 2016).
>
> U.S. Army: disqualified if scoliosis >20 degrees but routinely waived up to 25 degrees. (ASAMS, 2008).
>
> U.S. Air Force: disqualified if lumbar scoliosis is >20 degrees or thoracic scoliosis is >25 degrees. (ASAMS, 2008).

3.2 Body-Borne Equipment

Body-borne equipment neck pain sources that will be focused on are helmets, and helmet mounted sensor systems such as night vision goggles and helmet mounted displays. The fundamental concept relating helmet mass and neck pain was studied by Hoek van Dijke (1993) who developed a biomechanical model of F-16 pilot postures. He concluded that dangerous loads on the cervical spine could be significantly reduced by decreasing helmet weight and by shifting the helmet center of mass backwards to counter helmet-mounted devices. Burton et al. (1999) also recommends reducing the weight and load moments of loads on the head resulting from worn life-support equipment and protective systems.

In reference to the addition of helmet mounted sensors (i.e., more mass, potential centre of mass offset, and more inertia), Sarsfield, O'Hara, and Wright (2012) state that the current helmet-mounted cueing system leads to increased neck rotation during the check-six maneuver. The effects of adopting postures with high neck rotation are discussed in section 3.3**Error! Reference source not found.**. Two additional studies (Eveland, Esken, Shouse, Goodyear, & Kane, 2008; Mathys & Ferguson, 2012) discuss how improved helmet-mounted systems may be increasing performance, however the increased weight and changes to the center of mass of the head and helmet system may be more fatiguing.

Eveland et al. (2008) conducted a study designed to determine the effects of helmet system mass properties and used variable weight helmet testbeds to create three helmet conditions. The first condition represented a basic flight helmet (3.0 lb), and the two heavier conditions represented the Joint Helmet Mounted Cueing System (JHMCS) (4.5 lb), and the JHMCS variant with panoramic night vision goggles (PNVG) (6.0 lb). Their data collection methods were discussed in detail in section 2.3. Eveland et al. (2008) were able to show statistically significant results indicating muscle fatigue throughout their long duration test days, however each helmet condition fatigued similarly. Therefore, there were no significant differences in muscle fatigue between the helmet conditions. There was significant difference found between helmet conditions for a computer-based target recognition task, but it involved minimal muscle activity. The authors also question the importance of this finding due to their study design not controlling potential training effects.

Eveland et al. (2008) also reported on subjective survey responses and found that helmets with a forward center of mass were significantly more uncomfortable than helmets with a neutral center of mass regardless of helmet mass. Specifically, the 4.5 lb helmet with a more forward center of mass than the 6.0 lb helmet was significantly less comfortable. The discomfort was specific to the neck and back.

Despite the lack of significant quantitative results comparing between helmet conditions, Eveland et al. (2008) conclude that their results would serve as useful information for NVG development. They also suggest that a helmet condition heavier than 6 lb and with a more forward center of mass should be tested.

Thoolen (2015) also investigated the effect of the new Joint Helmet-Mounted Cuing System (JHMCS) on spinal complaints in F-16 pilots by undertaking a survey with 49 pilots who completed a similar survey in 2007, before the JHMCS. Survey results suggested that pilots associated the JHMCS (88%), NVGs (88%), type of flight (63%), and sitting posture (50%) with flight-related reports of neck pain.

Sovelius, Oksa, Rintala, Huhtala, and Siitonen (2008) investigated the neck muscle loading differences while wearing NVGs compared to not wearing NVGs. Their investigation was aimed at the problem of neck loading specific for military pilots that operate under high G accelerations, and their methods included generating high G accelerations using trampoline exercises. Participants of the study were 14 Finnish Air Force pilot cadets, with a mean age of 21.5 years. The trampoline exercises included basic, hand and knee, and back bouncing, where basic bouncing simulates low G_z loading, hand and knee bouncing simulated head extension while under $+G_z$, and back bouncing simulates rotation and/or lateral bending during a check-six maneuver. In reference to how the trampoline exercises compare to actual high-performance aircraft flight the authors report that based on a previous study the accelerations generated during trampoline exercises ranges from 0 to $+4\ G_z$ and during the current study muscle activation levels were similar to levels capture in-flight. Three helmet conditions were used no helmet (baseline), helmet (1.53 kg) and helmet plus NVGs (2.33 kg). EMG data was recorded for the sternocleidomastoid, cervical erector spinae, thoracic erector spinae, and trapezoid muscles. The EMG results were calculated as percent of isometric MVC.

Sovelius et al., (2008) found that there was a statistically significant increase in muscle loading between the helmet and no helmet condition for basic jumping. The increase was observed for the cervical erector spinae and trapezoid muscles. There was no statistically significant increase in muscle loading between the helmet and helmet plus NVG conditions for the basic jumping exercise. During back bouncing the authors found a significant increase in sternocleidomastoid and cervical erector spinae muscle loading when the helmet was added and a significant increase in sternocleidomastoid muscle loading when the NVGs were added. During hand and knee bouncing the authors report a significant increase in loading for all muscles, except the trapezoid, when the helmet was added, and an increase in both cervical and thoracic erector spinae muscles when the NVGs were added. In general, the authors discuss that the NVG device being mounted on the front of the helmet increases the flexor moment acting on the neck, increasing the required extensor muscle loads required to control the head posture and movements. The authors discuss how trampoline exercises could be used to train the neck muscles to hold the head posture during the first seconds of G_z loading.

To mitigate the effects of head born equipment Burton et al. (1999) investigate, prototype, and evaluate systems that provide mechanical support to the neck during high-G exposures while still enabling enough head movement to perform operational tasks. One category of support devices only activate at high G levels, which can be problematic because significant head range of motion is still necessary during increased G. An alternative device that the authors discuss only activates during involuntary head movement, but this approach can be problematic because it would not protect against external loads due to high G exposures when the head is static.

3.3 Aircrew Behaviour

Aircraft behaviour sources of neck pain refers to what aircrew do, including details of postures adopted during flight. Coakwell, Bloswick, & Moser, Jr., (2004) state high performance aircraft pilots adopt postures that compromise the cervical geometry and are associated with reported neck injuries. They define the criteria of compromised cervical geometry to be spinal canal narrowing, neuroforaminal narrowing and pressure increases, intervertebral disk compression and twisting, increased intradiscal pressures, and awkward alignment of the vertebrae. They continue to state that when cervical geometry is compromised and forces are increased, the risk of neck injury is also increased. Sarsfield, O'Hara, and Wright (2012) discuss how the neck is capable of sustaining high axial loads, however loads on the cervical spine during defense or offensive maneuvers are not often in the axial direction. When a posture outside of the neutral posture is adopted the moment arm of the head and helmet mass can produce high forces within the neck structures. Shiri, Frilander, Sainio, Karvala, Sovelius, Vehmas, and Viikari-Juntura (2014) state that awkward neck posture may be the most important contributing factor to neck pain of high-performance aircraft pilots.

The most common high-risk maneuver discussed in the literature is "check-six" (Coakwell et al., 2004; Shiri et al., 2014; Burton et al., 1999). Shiri et al., (2014) conducted a meta-analysis of the literature report that the check-six posture was the most common one associated with neck pain. Burton et al. (1999) noted that extreme head rotation of the check-six maneuver places greater demands on the extensor muscles and requires the recruitment of comparatively weaker muscles that are more exposed to injury.

Coakwell et al. (2004) used neck biomechanics and geometry to define additional high-risk head and neck movements for high performance aircraft pilots. Their four additional high-risk movements were: rotation beyond 35°, lateral bending, extension beyond 30°, and flexion beyond 15°. The authors report that C7-T1 joint reaction forces under high G_z, while the neck is rotated, increase by a factor of 15 and the threshold for a drastic increase in joint reaction forces has been reported at 35°. They reference a cause of injury being spinal column narrowing when neck rotation is combined with extension of the neck. In reference to lateral bending, the authors report that a dramatic increase in C7-T1 joint reaction forces is observed at a movement beyond 0°. The authors suggest that lateral neck muscle activity is highest compared to other muscle groups during high performance flight, but conversely lateral neck muscles have less isometric endurance. Increased strain on the intervertebral disks has also been linked to lateral bending combined with rotation and axial compression. In reference to extension beyond 30°, the authors to discuss this as a high-risk posture because it is an inflection point for a rapid increase in joint reaction forces, the anterior neck muscles have been shown to have the lowest endurance time of all muscle groups, and x-axis shear has been shown to increase significantly with neck extension. The authors discuss flexion beyond 15° as a high-risk posture because it is an inflection point for rapid increase in joint reaction forces, there is an increase in the lever arm of the head mass and therefore increased neck moments, the muscle group has a decreased force-generating capacity, and decreased efficiency. The authors describe the "checking six" posture as the action of the pilot looking directly behind the aircraft. It often involves a combination of maximal rotation, flexion or extension, and lateral bending. The individual detriments of these movements have been discussed and the authors conclude that the combination of factors during this maneuver cause pilots to be at a very high risk for injury.

Coakwell et al. (2004) discuss a few preventative measures for neck pain that relate to aircrew behaviour. They include minimizing head movement, using an external support for the head and neck, pre-positioning the head before exposure to $+G_z$ acceleration, and "unloading" the G forces on the aircraft prior to moving the neck. Their discussion about minimizing head movement referred generally to any position out of the neutral posture. The example sources for head support included the canopy of the aircraft and seat back, and they specifically suggest using the head support during high $+G_z$ accelerations. Pre-positioning the head refers to putting the head in the desired direction of gaze prior to the $+G_z$ acceleration. Limiting head movement, head supports and pre-positioning the head was also discussed by Burton et al. (1999). Albano (1998) reported a statistically significant decrease in neck injuries among F-16 pilots who braced their heads against the seat prior to a high-G maneuver, positioned their heads in the desired directing of gaze to the onset of high-G, and waited to unload +G forces prior to moving their heads after a maneuver. Similarly, Green (2004) found that the extent of neck muscle activation during combat was reduced by 50% when the pilot used the canopy to support their head during high-G maneuvers. A survey of Royal Australian Air Force fighter pilots reported the use of head positioning prior to the application of G_z and using aircraft structures to brace their heads as personal neck stress reduction strategies (Newman, 1997).

Jones (2000) noted that cervical injury incidence seemed to present in bimodal peaks: the first occurring early in a pilot's career before they have learned avoidance techniques and later in their career (> 1000 flight hours) when accumulated effects begin to present damage to neck structures. Pilots are encouraged to learn head bracing techniques prior to entering into high-G maneuvers to reduce the risk of injury.

In contrast Tucker et al. (2014) reported that a pilot's use of preventative actions was positively correlated with neck pain after flight. The preventative actions included bracing the head against both the canopy and ejection seat head box, and restricting movement under G_z. The authors discuss how the positive correlation is surprising and two possible explanations are: the preventative actions themselves require significant muscle activation causing them to become more fatigued, and that pilots who had already experienced neck pain may use preventative actions more frequently.

3.4 Aircraft Workspace

Aircraft workspace sources of neck pain refers to where the aircrew work including cockpit and seat design, as well as the performance capabilities of the aircraft itself. Cockpit and seat design will factor into the postures that pilots are required to adopt as discussed in section 3.3 and the performance capabilities of the aircraft will be directly linked to the G acceleration levels that can be reached.

A Group of authors that conducted a literature review on the relevant biomechanical factors of high performance flying summarized force exposure during air combat maneuvers (ACM) (Coakwell, Bloswick, & Moser, Jr., 2004). They summarized results from the F/A-18, F-16, and Hawk 51 or 51A, in regard to sortie length, number of excursions above 2 G_z, average time per excursion above 2 G_z, total time above 4 G_z, average number of excursions above 4.5 G_z, number of peak strain episodes of posterior neck muscles, and number of peak strain episodes of lateral neck muscles. For the F/A-18 the authors reported a range of combat maneuver sortie length from 33.6 to 53.9 minutes, a range of excursions above +2 G_z from 37 to 61, a range of average time per excursion above +2 G_z from 7.8 to 8.3 seconds, and a range of total time above +4 G_z from 1.2 to 2.3 minutes. The authors report that for F-16 air combat maneuver sorties there was 49% of the total time spent under +2 G_z and 5% of the total spent over +7 G_z. For the Hawk 51 or 51A the authors reported a sortie duration range from 26 to 36 minutes, an average number of excursions above 4.5 G_z of 38, a range of peak strain episodes of posterior neck muscles from 10 to 18, and a range of peak strain episodes of lateral neck muscles from 10 to 85. The authors state that high performance aircraft pilots are at risk of musculoskeletal disorders due to the high forces at a high rate of repetition.

Sarsfield, O'Hara, and Wright (2012) also report that F-16 flight often reaches 8 G_z loading and when the head and helmet mass are taken into consideration the neck is required to withstand G_z forces up to 9 G_z.

An important piece of high performance aircraft design is seat-back angle. Coakwell et al. (2004) review studies that have investigated the impact of changing the pilot's seat back angle. The reason seat-back angle is a concern is because when the seat has a backward inclination there is more flexion required at the neck causing increased loading on the cervical spine. One study reviewed by Coakwell et al. reports a 3.6-times increase in the load moment at the C7-T1 joint with a reclined position compared to a neutral position. The cause of the increased moment is due to the increase in moment arm from the C7-T1 joint to the center of mass of the head and helmet. In reference to the muscle and ligaments of the cervical spine the increased flexion will also lengthen the dorsal neck muscles, which leads to a decrease force-generating capacity and efficiency (Coakwell et al., 2004). Two other groups of authors supported these findings, for example Hoek van Dijke (1993) developed a biomechanical neck model to F-16 seated postures and found that the more reclined backrest of the F-16 seat reduced cervical lordosis. Jones (2000) suggested that the more reclined backrest angle of the F-16 may account for the higher incidence of neck injury over aircraft with more upright backrests (i.e. F-14 and F-15).

In reference to mitigating strategies Jones (2000) recommend the development of better head/neck bracing supports as well as better hand/arm support rails to encourage better upper torso bracing within the pilot workspace. Burton et al., (1999) suggest developing pilot seats that support the head and neck.

3.5 Organization

Organisation sources of neck pain refer to elements of when and why high-performance aircraft pilots fly including factors such as mission durations, mission frequencies, and maneuver frequencies within a mission. Organisation sources of neck pain often relate to muscle fatigue and cumulative effects of high G acceleration exposure.

Coakwell, Bloswick, & Moser, Jr., (2004) summarized $+G_z$ force exposures during air combat maneuvers from the literature and discuss the importance of the cumulative effects of high G accelerations. They specifically make the connection between high performance aircraft G force exposures and the two work-related musculoskeletal disorder risk factors: high force and high repetition. Their methods and findings were discussed in section 3.4 as they provide a good review the different types of G force exposures that have been reported amongst a few of the high-performance aircraft. In relation to organisation sources there is also a connection to their findings because they also highlight the potential cumulative effects given typical air combat maneuver sorties.

One group of authors that were focused on understanding the cumulative effects of G acceleration exposure was Kang, Hwang, Lee, Tang, and Park (2011). They reported on surveys completed by 1085 active pilots from the Republic of Korea Air Force and one of their aims was to obtain a better understanding of the relationship between neck pain and G_{max} level as well as the amount of G_{max} exposure. Their first important finding that relates to the cumulative effects of high G acceleration exposure was that both the frequency of G_{max} and monthly duration of G_{max} exposure were correlated with whether the aviator had experienced neck pain, the frequency of neck pain and the severity of neck pain. The second important finding relating to cumulative effects was that for the aviators exposed to high G accelerations there was no significant difference in neck pain in relation to the G_{max} level, but there was a significant difference in relation to amount of G_{max} exposure. This led the authors to conclude that above a certain G level there is a ceiling effect on neck pain and the amount G_{max} exposure becomes more impactful on neck pain.

Placentino (2017) noted that limiting pilot exposure frequency and duration to high-G exposures can be difficult to apply in a military context but there remains scope for a broader administrative management of total exposures over time. Taking the broader view, Placentino suggests that mission planning could ensure a more balanced distribution of high-G flights among pilots, a more balanced exposure of high and low-G flight operations, and an allowance for adequate recovery time between flights. Low-G flights could also be used constructively as a means of managing a pain occurrence from a previous flight to provide the pilot with more recovery time, as a return-to-work rehabilitation step before return to high-G flight operations, and as a way to provide a working 'rest' from high-G flying.

Another factor that may have an impact on mission planning is ambient operating temperature. Sovelius, Oksa, Rintala, Huhtala, and Siitonen (2007) conducted a study with 24 Finnish Air Force pilot cadets to test the hypothesis that cold-induced increase in muscle strain may lead to in-flight neck injuries. The authors simulated high G accelerations (0 to $+4\ G_z$) using two trampoline exercises: basic bouncing and hand and knee bouncing. Two different ambient temperatures were tested in the study, -2 degrees and 21 degrees, and participants were exposed to the temperature for 30 minutes prior to completing the trampoline exercises. Skin temperature was recorded at the sternocleidomastoid and trapezoid during the 30-minute pre-exercise exposure and throughout the exercises themselves. The authors report a significant decrease in surface temperature at both muscle sites when exposed to the -2 degrees ambient temperature. Surface EMG data was recorded during the trampoline exercises and the authors report that there was significantly higher muscle loading

(%MVC) when the exercises were completed with a -2 degrees ambient temperature. This result was found with the cervical muscle, sternocleidomastoid and cervical erector spinae, but not with the lower muscle that were more covered with clothing, the thoracic erector spinae and trapezoid. The authors provide operational relevance by also reporting a significant decrease in trapezoid skin temperature during pre-flight activity of walking to the aircraft, conducting pre-flight checks and closing the canopy. They go on to make the connection that the higher muscle activation levels reported during the trampoline exercises in colder temperatures suggests that there would be higher muscle activation levels for pilots exposed to colder ambient temperatures during pre-flight activities. They suggest that countermeasures should be taken to buffer the skin temperature cooling of pilots before takeoff.

As a mitigating strategy Placentino (2017) suggests that pilots of high-performance aircraft should be managed like professional athletes. Using the Professional Athlete Model (PAM), pilots would have ready access to flight surgeons, exercise specialists, physiotherapists, and psychologists. In this model, the 'athlete' support team would monitor the pilot's physical and mental preparedness for flight, provide customized warm-ups and physical development, and ensure rapid, preventative, and rehabilitative interventions as soon as problems arise.

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High G-induced neck injuries are common in high-performance fighter aircraft. A review of the incidence literature on the association between neck pain and flying high-performance military aircraft highlights that this is a significant problem that crosses nations and aircraft types. A literature review was conducted for Defence Research and Development Canada (DRDC) Toronto Research Center (TRC) as part of the planning process for the future Fast Jet Aircrew Neck- and Back-trouble Mitigating Solutions research project 03eb02. The focus of the literature was on the epidemiology, methods used to model neck pain for fast jet aircrew and the neck pain sources and mitigation strategies. A set of keywords was developed and used to search online databases.

The first component necessary for modeling neck pain sources of fast jet aircrew is understanding the effects of high accelerations on the body. The body behaves differently depending on the direction of the G force however the impact on the body is a combination of the physical force and blood being either drained or forced into different parts of the body. Correlating subjective survey data is the most common method used to model neck pain sources, however addition methods include neck loading data collection with instrumentation such as accelerometers and electromyography sensors, and biomechanical modeling.

Sources and mitigating strategies were organised into operator factors, body-borne equipment, aircrew behaviour, aircraft workspace and organisation factors. Operator factors focused on the relationships between demographic characteristics and neck pain including scoliosis, age, sex, anthropometry, flying history and muscle strength. Body-borne equipment was focused on helmets, and helmet mounted sensor systems and the impact of changing neck supported mass characteristics. Aircrew behaviour sources of neck pain and mitigating strategies related to body postures adopted during flight and the impact they have on neck loading. Aircraft workspace sources include cockpit and seat design as well as the performance capabilities of the aircraft itself. The cockpit and seat design factor into the postures adopted and the performance of the aircraft is linked to the G acceleration levels that can be reached. Organisation sources of neck pain refer to elements of when and why high-performance aircraft pilots fly including factors such as mission durations, mission frequencies, and maneuver frequencies within a mission. Organisation sources of neck pain often relate to muscle fatigue and cumulative effects of high G acceleration exposure

Les blessures au cou induites par un taux de G élevé sont courantes dans les avions de combat hautes performances. Une revue de la littérature sur l'incidence sur l'association entre douleur au cou et le vol d'aéronefs militaires à hautes performances montre qu'il s'agit d'un problème majeur qui touche différents pays et types d'aéronefs. Une analyse documentaire a été réalisée pour le Centre de recherches de Toronto (CRT) par Recherche et développement pour la défense Canada (RDDC) dans le cadre du processus de planification du futur projet de recherche 03eb02 s'appellé « Fast Air Neck- and Back-trouble Mitigating Solutions ». La littérature s'est concentrée sur l'épidémiologie, les méthodes utilisées pour modéliser les douleurs au cou chez les membres d'équipage à réaction rapide et les sources de douleurs au cou, et les stratégies d'atténuation. Un ensemble de mots-clés a été développé et utilisé pour rechercher des bases de données en ligne.

Le premier élément nécessaire pour modéliser les sources de douleurs au cou des équipages d'aéronefs à réaction rapide consiste à comprendre les effets des fortes accélérations sur le corps. Le corps se comporte différemment selon la direction de la force G, mais l'impact sur le corps est une combinaison de la force physique et du sang drainé ou forcé dans différentes parties du corps. Les enquêtes subjectives sont les méthodes les plus couramment utilisées pour identifier et éventuellement modéliser les sources de douleur au cou. Cependant, les méthodes supplémentaires incluent la collecte de données sur la charge du cou avec des instruments tels que des accéléromètres et des capteurs électromyographiques, ainsi que la

modélisation biomécanique.

Les sources et les stratégies d'atténuation ont été organisées sous la forme de facteurs opérateurs, d'équipements embarqués, de comportement des équipages, d'espace de travail, et des facteurs de l'organisation. Les facteurs opérateurs étaient concentrés sur les relations entre les caractéristiques démographiques et les douleurs au cou, notamment la scoliose, l'âge, le sexe, l'anthropométrie, les antécédents de vol et la force musculaire. Les équipements portés par le corps étaient concentrés sur les casques, les systèmes de capteurs montés sur les casques et l'impact des caractéristiques de masse changeantes soutenues par le cou. Comportement des équipages en cas de douleurs au cou et stratégies d'atténuation liées aux postures corporelles adoptées en vol et à l'impact qu'elles ont sur la charge cervicale. Les sources d'espace de travail de l'avion comprennent la conception du poste de pilotage et des sièges, ainsi que les performances de l'avion lui-même. Les facteurs du poste de pilotage et de la conception des sièges prennent en compte les postures adoptées et la performance de l'avion est liée aux niveaux d'accélération G pouvant être atteints. Les sources organisationnelles de cervicalgie font référence au moment et aux raisons pour lesquels les pilotes d'aéronefs performants volent, y compris à des facteurs tels que la durée des missions, la fréquence des missions, les fréquences de manœuvre au sein d'une mission. Les sources organisationnelles de douleur au cou sont souvent liées à la fatigue musculaire et aux effets cumulatifs d'une exposition à une accélération élevée du G.