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Surgical Interventions for Cervical Intervertebral Disc Disease in U.S. Army Aviators: A Comprehensive Review and Identification of Knowledge Gaps

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14. ABSTRACT
Two common cervical spine surgical intervention procedures (CSSIPs) for treating patients with severe cervical spine intervertebral disc disease (CIDD) are anterior cervical discectomy and fusion (ACDF) and cervical disc arthroplasty (CDA). Most medical guidelines regarding ACDFs and CDAs are based on general population health, activities, and life expectancy. Presently, knowledge gaps exist related to CCSIPs in the context of operational activities of military personnel who are frequently exposed to more dynamic and physically demanding scenarios than the general population. Currently, military guidelines consider ACDF and CDA disqualifying conditions for military fitness. This work presents the results of a robust literature review updating the state of knowledge regarding CSSIPs used for the treatment of CIDD and their applicability to the U.S. military rotary-wing environment.

15. SUBJECT TERMS
Cervical spine, cervical spine surgical intervention, cervical spine intervertebral disc disease, CIDD, Anterior cervical discectomy fusion, ACDF, cervical spine fusion, cervical disk arthroplasty, CDA, cervical spine surgical intervention procedures, CSSIPs, functional spine unit, FSU, Prestige ST®, Prodisc-C®, Bryan®, Secure-C®, PCM®, Mobi-C®, Prestige LP®, M6-C®, Simplify®

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Summary

Rotary-wing aircraft operations create unique dynamic, mechanical loadings on aviators. Vibration in aviation environments can be complex; it is comprised of the internal motion of aircraft parts and the varying external effects associated with air travel or motion. These occupational exposures, in conjunction with repeated jolt and shock, helmet systems, and impacts during mishaps, place military personnel at high risk for severe cervical spine intervertebral disc disease (CIDD) requiring surgical intervention. Spine-associated symptomology and pathology have been a well-recognized health concern for military aviators in fixed- and rotary-wing platforms for over 50 years. Spinal injuries and disorders result in thousands of lost work hours for military aviators and significant health care costs to diagnose and treat these issues. The development of effective treatment options is necessary to improve medical readiness, retention, and endurance of military aviators with spinal injury and disorders.

Cervical spine surgical intervention procedures (CSSIPs) are used to treat patients who present with symptoms associated with severe CIDD, such as radiculopathy, myelopathy, and neck pain. Two common CSSIPs are anterior cervical discectomy and fusion (ACDF) and cervical disc arthroplasty (CDA). The ACDF procedure is commonly referred to as the "gold standard" CSSIP; however, the main advantage of CDA over ACDF is the retention of more natural cervical spine biomechanics. While an increasing number of U.S. Army aviators are receiving the CDA procedure, the option of CDA as a CSSIP presents new questions regarding military aviation populations because of their exposure to unique environments and occupational conditions.

Military aviators who elect to have CSSIPs are potentially disqualified from flight status under current aeromedical practices. The effects and return to duty (RTD) outcomes of these treatments have been studied in civilian and military populations. However, little research exists to evaluate their use in the harsh operating environments of military aviators. Furthermore, all RTD data related to outcomes for civilian and military populations were determined via predictive surveys of surgeons or retrospective reviews of medical health records and database sources. There are still significant gaps in the knowledge base regarding the full impact of these procedures once the aviator returns to duty in a military aviation environment, such as the performance of these surgical implant devices in the dynamic environment and resulting cervical spine response in high vertical load "G" forces typically seen in rotary-wing crash environments and mishaps.

The initial investigation and consideration regarding the use and impact of CDA as a CSSIP treatment option in military populations began in 2007 after the U.S. Food and Drug Administration (FDA) approved the first cervical disc implant. The CDA procedures have evolved, and advancements have been made in the surgical technique, implant designs, and biomaterials. Researchers at the U.S. Army Aeromedical Research Laboratory (USAARL) and the Medical College of Wisconsin/Clement J. Zablocki Veterans Affairs Medical Center (MCW/VAMC) have recently taken on the task of investigating the long-term function and effects following CSSIPs, specifically CDA, and its applicability to military aviation populations using animal and computational models. Although this report does review and discuss CDA procedures and outcomes, it does not individually review nor provide recommendations on the various CDA implants.

The USAARL conducted a comprehensive literature review on the current state of CSSIPs in civilian and military aviation populations. The literature review resulted in the recommendation of research strategies, approaches, and methodologies that are essential for determining the rationale for the surgical choice between these two types of CSSIPs, development of fitness for RTD standard guidelines, and updating the aeromedical policies related to CSSIPs to ensure and maintain medically fit military aviators. The recommendations are outlined in Madison et al.'s report: USAARL-TECH-SR--2023-06 (2022). This work is necessary to provide the framework for better-informed medical guidance related to assessing and treating severe CIDD in military populations. The outcomes from the recommended research strategies will address the knowledge gaps in U.S. Army aviation and in aviation personnel across all military branches, domestic and international, and civilian populations.

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Introduction

Occupational exposures, such as those due to vibration, repeated jolt and shock, head supported mass (HSM) like helmet-mounted devices, and impacts during mishaps, place military aviators at high risk for severe cervical spine intervertebral disc disease (CIDD) requiring surgical intervention. Neck pain and cervical disc degeneration resulting from CIDD are well documented in military personnel and have resulted in thousands of lost work hours and significant costs in diagnosing and treating these issues. Severity of injury or disease may range from mild soreness and pain to severe degeneration needing surgical intervention. The ultimate cost must also account for the expense of training personnel to replace injured aviators and the loss of their invaluable knowledge and experience. Hamon et al. (2012) estimated the cost of neck/back/leg pain to the Department of Defense (DoD) to be nearly $240 million annually. Estimated costs for military basic flight training are around $1 million per pilot, with costs totaling greater than $9 million for required and/or advanced training over the course of a military career (Gebicke & Farrell, 1999). Therefore, it is more cost effective to investigate, develop, and leverage prevention, mitigation, and treatment options for our aviators that maintain their medical readiness and operational endurance.

Anterior cervical discectomy and fusion (ACDF), commonly known as cervical spine fusion, and cervical disc arthroplasty (CDA) are the two cervical spine surgical intervention procedures (CSSIPs) used for the treatment of severe CIDD. Cervical spine fusion was once the "gold standard" CSSIP; however, this procedure can cause accelerated degeneration in the adjoining intervertebral discs (IVD) that could cause the aviator to require further surgical treatment. This complication is referred to as adjacent segment degeneration or disease (ASD). As a result, CDA is gaining popularity over ACDF as an alternative for the treatment of severe, symptomatic CIDD. A main advantage of CDA as a CSSIP is the retention of more natural cervical spine motion. The replacement disc used in CDA is intended to mimic the natural form and function of an IVD; therefore, the procedure may better resolve the occurrence and symptoms of CIDD-induced radiculopathy, myelopathy, and neck pain without as deleterious effects on adjacent segments as ACDF.

Many medical guidelines regarding ACDF and CDA are based on general population health, activities, and life expectancy. However, operational activities of military personnel are more dynamic and concentrated than general populations and military personnel frequently experience accelerated CIDD. Current military aeromedical practice considers both ACDF and CDA disqualifying (U.S. Department of the Army [DA], 2019; Naval Aerospace Medical Institute [NAMI], 2022; U.S. Department of the Air Force [USAF], 2022); however, there are still significant gaps in the knowledge base regarding the full impact of these procedures when operating in a military aviation environment.

Current efforts at the U.S. Army Aeromedical Research Laboratory (USAARL) aim to update the state of knowledge regarding CSSIPs used for the treatment of CIDD and examine applicability of these techniques to treat military populations, a necessary first step towards gathering critical information needed to update and improve medical guidelines for military fitness for duty following cervical spine CSSIPs. A comprehensive literature review was conducted on the current state of CSSIPs in both civilian and military aviation populations. Additionally, updated epidemiological data were obtained regarding the incidence and prevalence of cervical spine pain, injury, disease, and disorder in aviation populations. For the purpose of this report, cervical spinal disorder will encompass any pain, injury, and disease in the neck or cervical spine. Using this information, preliminary assessments, and comparisons between ACDF and CDA were conducted based on multiple factors related to safety, efficacy, and military population compatibility. The outcomes of this work, with research recommendations detailed in a separate report (Madison et al., 2022), provide the framework to address the identified knowledge gaps for better-informed medical guidance related to the assessment and treatment options for severe cervical disc disease in military aviation populations.

Cervical Spine Pain, Injury, Disease, and Disorder in Military Aviation Populations

Anecdotal reports from U.S. military mounted (aviation and ground vehicles) personnel are increasingly pointing towards a growing suspicion that military occupations create, predispose, and/or exacerbate CIDD. According to a 2005 survey of the Total Army Injury and Health Outcomes Database (TAIHOD), more than 1.2 million neck- and back-related injuries were documented among U.S. Army personnel between 1980 and 2002. Additionally, the Defense Medical Surveillance System (DMSS) reported that the vertebral/back region was the top anatomical location associated with air-evacuated non-battle injuries in Afghanistan (2001-2006) and Iraq (2003-2006). Based on data queried between 2005 and 2015 in the Defense Medical Epidemiology Database (DMED) (Armed Forces Health Surveillance Branch [AFHSB], 2022), spinal diagnoses were consistently ranked in the top five most frequent causes for ambulatory visits and hospitalizations. These injuries have resulted in over one million outpatient visits and 1218 disability evaluations (Amoroso et al., 2005). The overwhelming majority of outpatient visits were for neck pain with diagnoses ranging from intervertebral disc disorders, spondylosis with myelopathy, and segmental or somatic dysfunction (Amoroso et al., 2005).

In pilots, tactical operations officers, and Special Forces members, these disorders are ranked even higher, with multiple studies reporting on the neck pain experienced and localized symptoms (Aydoğ et al., 2004; Bridger et al., 2002; Mason et al., 1996; Pippig & Kriebel, 2000). Spine-associated symptomology and pathology has been a well-recognized health concern for military aviators in both fixed- and rotary-wing platforms for over 50 years (e.g., Froom et al., 1987; Hämäläinen et al., 1999; Hämäläinen et al., 1996; Hodgdon et al., 1997; Landau et al., 2006; Mason et al., 1995; Orsello et al., 2013; Shanahan & Reading, 1985). Furthermore, reports show that neck pain is more prevalent (43-48%) in rotary-wing pilots compared to other military occupational specialties (MOSs) within the U.S. military, additionally, approximately 20% of rotary-wing pilots experience recurring or continuous neck pain (Bridger et al., 2002; Van den Oord et al., 2010).

Our review of data from DMED reported more Soldiers in operations and operations support are seeking treatment for back pain/injury than Soldiers in functional support and administrative MOSs. Furthermore, back pain/injury onset is occurring earlier, at less than 30 years of age, in operations and operations support MOSs than in functional support and administrative MOSs. Amongst U.S. Army helicopter pilots aged 20 to 24, neck pain and cervical disc degeneration ambulatory visits occur at rate of 31.23 per 1000 persons per year; for pilots aged 25 to 29, the rate is more than doubled. As the pilot age increases, so does the rate of degradation. Compared to pilots aged 20 to 24, ambulatory visit rates for helicopter pilots are almost seven times greater in those aged 30 to 34, ten times greater in pilots aged 35 to 39, and over twenty times greater in those age 40 and over. It is believed that the rates among fixed-wing tactical jet pilots are smaller yet still operationally significant (Lang et al., 2022).

Cervical Spine Intervertebral Disc Disease: Pathology, Symptomology, and Treatment

Rotary-wing aviators have been shown to experience a significantly higher rate of cervical disorders than fixed-wing pilots and non-aviators (Aydog, 2004). Degeneration of the cervical spinal discs (for example, spondylosis) can result from continued exposure to vibration and HSM. Symptomatic CIDD is a functionally limiting degenerative condition of the cervical spine. Approximately 1 in every 1000 U.S. Army aviators have experienced symptomatic spondylosis (Mason, 1996).

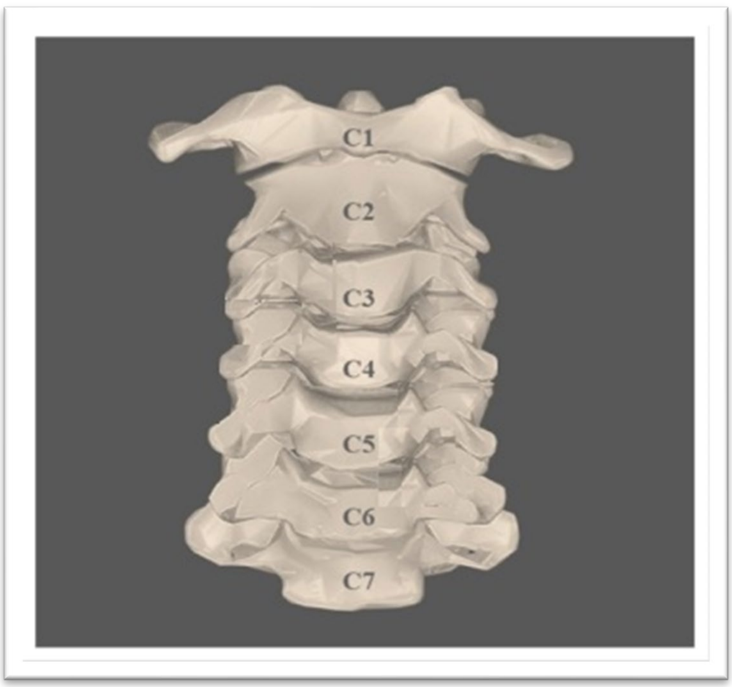

Figure 1. Anterior view of cervical spine with labeled vertebrae. Figure adapted from BodyParts3D (2013).

The cervical spine is composed of seven vertebral bodies (Figure 1). The first cervical vertebra (C1), sometimes called the atlas, articulates the neck to the base of the skull. The weight of the head is transferred to the neck through the lateral articulations between C1 and the second cervical vertebra (C2), also called the axis (Swartz et al., 2005). Inferior to C2, IVDs are located between each vertebra creating six motion segments that connect the head to the first thoracic vertebra (T1). The six motion segments are as follows: C2-C3, C3-C4, C4-C5, C5-C6, C6-C7, and C7-T1. The functions of the cervical IVDs are to transmit the load of the head through the neck and to provide some flexibility in flexion/extension and lateral bending. The two main components of an IVD are the nucleus pulpous and the annulus fibrosus (Figure 2). The nucleus pulpous contains collagen and elastin fibers. The annulus fibrosus have concentric rings with collagen fibers between each ring (Urban & Roberts, 2003).

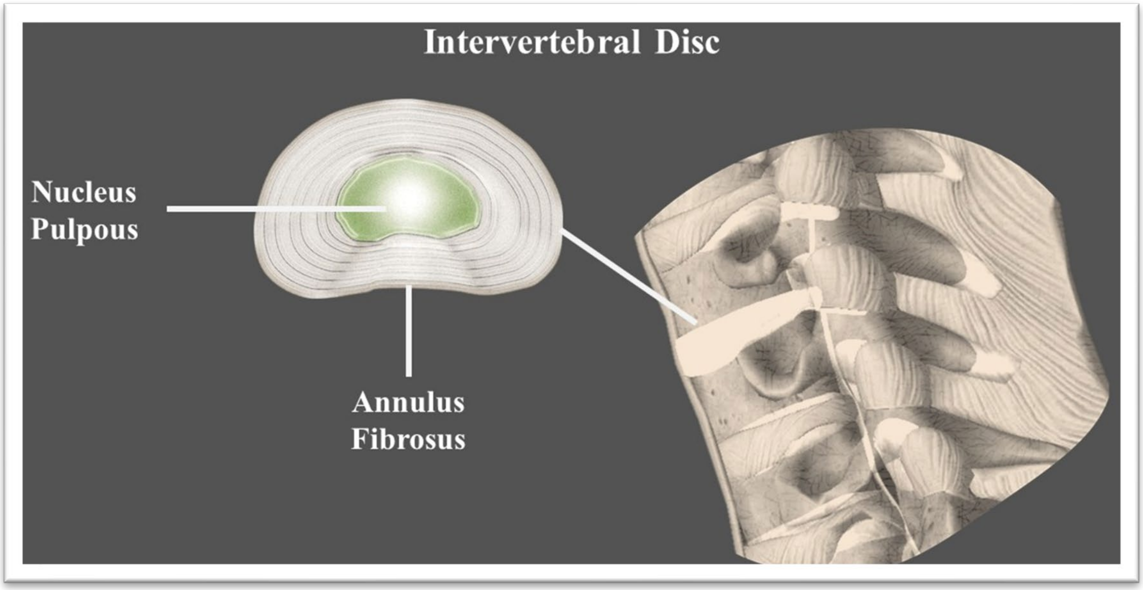

Figure 2. Intervertebral disc and components: Nucleus pulpous and annulus fibrosus. Figure adapted from 3D4Medical.com (2017).

Over time, the nucleus pulposus naturally degrades and is followed by a progressive degeneration of the annulus, sometimes causing an extrusion or herniation of the nucleus' components. The progression of degradation can also be exasperated by the operational exposures that aviators experience during flight operations. This break-down of the intervertebral space leads to a hypermobile and unstable segment of the spine. With these physiologic changes, the joints begin to experience altered loading that leads to hypertrophic changes, stiffness, and a decrease in cervical range of motion (CROM) (Fakhoury & Dowling, 2022), which is problematic as CROM is critical for safe and optimal operation of military aircraft (Williams et al., 2022a; Williams et al., 2022b). In general, three common repetitive cervical motions for aviation Soldier are flexion, extension, and axial rotation; these cervical motions are critical in aviation environments while conducting flight or aircraft maneuvers and tasks.

Overall, treatment approaches for cervical disc disease are centered around decreasing pain, improving function, and minimizing recurrence and duration of symptoms. Non-surgical treatments currently in place for CIDD rarely result in complete pain relief and are not considered permanent or long-term solutions. As a result, approaches for treatment strategies typically begin with non-surgical care and ultimately lead to surgical intervention.

Degeneration of the cervical spine can be separated into three different stages: dysfunction, instability, and stabilization (Fakhoury & Dowling, 2022). During the dysfunction stage, there may be tears present that are radial and circumferential along the annulus. While these are generally mild cases, military aviators may begin to feel a difference in their physical state. Strengthening exercises, lifestyle changes, and medical profiling are used as treatment or management strategies. Researchers within the U.S. military have proposed a fitness regimen for military pilots to treat and prevent neck pain and injury (Novotny et al., 2021; Wade et al., 2021), and the U.S. Air Force (USAF) has enacted personalized healthcare to treat neck pain and injury for its fighter pilot units (Pawlyk, 2019). Once the degenerative process of the spine progresses past minor tears along the annulus and into the inner disc, combined with progressive resorption and facet joint degradation, the motion segment is in the instability stage. Medical treatment is sought at this stage. Moderate cases may be managed with injections. The possibility of post-injury mitigation for more severe injury cases is very limited and typically requires surgical intervention when other treatment methods no longer relieve the pain and discomfort from symptoms or complications of cervical degradation. Surgical intervention is often the only way to get to the stabilization stage.

Cervical Spine Surgical Intervention Procedures

CSSIPs are used to treat patients who present with radiculopathy, myelopathy, and neck pain. Radiculopathy refers to a variety of symptoms resulting from a pinched spinal column nerve root. A change or reduction in intervertebral disc height is a leading cause of radiculopathy; weakness, numbness, and tingling are the most common reported symptoms. Myelopathy describes a compression spinal cord injury (SCI) resulting in disc herniation or degenerative disease. In addition to pain in the back, neck, and arms, reported symptoms may include weakness, numbness, and tingling; difficulty with fine motor skills and walking, erratic (increased or abnormal) reflexes, or sensory in the extremities. Ideal candidates for CSSIPs are those who have failed to respond to conservative non-invasive therapy options, such as physical therapy, anti-inflammatory medications, analgesics, injection therapy, and axial traction. ACDF, commonly known as cervical spine fusion, and CDA are the two CSSIPs used for the treatment of severe CIDD. The intervertebral space between C5 and C6 has the highest rate of surgical intervention, followed by the space between C6 and C7 (Miller et al., 2018; Fakhoury & Dowling, 2022).

Anterior Cervical Discectomy and Fusion

ACDF is a two-part surgical procedure to remove a damaged cervical spine disc from between two vertebral bodies within a motion segment. The ACDF procedure can be performed for a single-level at multiple levels within the cervical spine; however, single-level and two-level ACDF are the most common (De la Garza-Ramos et al., 2016). After the damaged disc is removed, natural disc space between the adjacent vertebral bodies should be maintained. This can be facilitated through the use of a spinal cage spacer implant. The cage can be made of metal, ceramic, or a polymer; titanium and polyetheretherketone are the most used materials. A bone graft, which is required for the ‘fusion’ of the adjacent vertebral bodies, will be inserted into the vacant disc space (inside the cage if used) to stimulate bone growth between the vertebrae. The bone graft source can be an autograft (i.e., the patient’s own tissue) from the iliac crest, allograft from a donor, or other graft materials. The cages are cylindrical shaped and porous to help facilitate the bone fusion (Jain et al., 2016). Fusion eliminates motion and ultimately stabilizes the affected motion segment. Plates and screws are usually used to assist with stabilization of the vertebral layers (North American Spine Society [NASS], 2015). According to a systematic review and meta-analysis study by Oliver et al. (2018), anterior plate fixation with ACDF is associated with significantly higher vertebral fusion and notably lower cage subsidence, or reduction in the vertical vertebral disc space height, compared to ACDF without anterior plate fixation.

Cervical spine fusion was once the "gold standard" surgical procedure for treatment of severe cervical spine disease. However, studies suggest that the stabilization of the motion segment can cause harmful long-term effects on adjacent motion segments resulting in instability, which could require further surgical treatment; this complication is known as adjacent segment degeneration or disease (ASD) (Bohlman et al., 1993; Goffin et al., 1995). Research specifically focused on the development and prevention of symptomatic ASD identified a common incidence rate of 2.9% per year. Newly developed ASD was also found to result in the onset of radiculopathy or myelopathy severe enough to require surgery. Approximately 25.6% of patients developed new ASD within 10 years of their initial cervical spinal fusion procedure (Hilibrand et al., 1999; Hilibrand & Robbins, 2004). Furthermore, medical professionals at Vanderbilt Health have anecdotally reported that approximately 20% of cervical fusion recipients have some pain or difficulties post-surgery. This has been attributed to nerve irritation resulting from small movements of unfused bone.

Current research is investigating the etiology of ASD and whether the number of fusion levels from ACDF, surgical instrumentation, or the pre-existence of ASD significantly attributes to ASD post-ACDF surgery (Shin, 2019; Chen et al., 2021; Peng et al., 2022). Additionally, researchers are investigating whether the forced increased motion of the non-operated (adjacent) cervical motion segments after ACDF (particularly single-level) are progressing the degeneration of adjacent segments (Choi et al., 2019; Shin, 2019; Delamarter & Zigler, 2013; Buttermann, 2018). However, there are some conflicting results on whether single-level versus multilevel ACDF progresses the rate of ASD (De la Garza-Ramos et al., 2016).

It is known that ACDF limits some range of motion (ROM) in the cervical spine at the level of the ACDF and overall CROM. Nonetheless, ACDF is still considered very successful in decreasing cervical pain and improving quality of life. Buttermann (2018) found that at a minimum ten-year follow-up, subjective pain measures for patients undergoing ACDF for various segment levels significantly improved, and the self-reported surgical success ranged from 85 to 95%. Wu et al. (2012) reported that patients who received three- and four-level ACDF had obvious decreased CROM, but they would likely not have difficulties in performing the activities of daily living. However, it is unknown if this would hold true for military aviation operational environments.

Cervical Disc Arthroplasty

Published data show that patients undergoing ACDF experience some limited CROM due to the fusion of the diseased segment with greater limits on motion correlating to the number of levels fused (Wu et al., 2012). To preserve the range of cervical motion, CDA is gaining popularity as an alternative to standard ACDF as a CSSIP for the treatment of severe, symptomatic CIDD. Although the premise of CDA also involves damaged cervical spine disc removal, an artificial disc is inserted to replace the damaged disc.

The first artificial disc, a metallic sphere, was implanted with the intervertebral disc (IVD) space in the cervical spine in 1966 (Fernström, 1966). In 1991, 20 patients received vertebral disc replacement surgery using artificial disc implants comprised of a metal-on-metal articulating coupling mechanism with screws to the inferior vertebral bodies; in one case, the implant remained in vivo for 12 years (Porchet & Metcalf, 2004). Early versions of the CDA procedure required complete ligation/reduction of the anterior longitudinal ligament (ALL). With increasing surgical skill and experience, as well as subsequent improvements with technique and the introduction of microscopic and arthroscopic procedures, complete resection of the ALL is seldom, if ever performed. The replacement disc used in CDA is designed to mimic natural form and function; therefore, the procedure may better resolve the occurrence and symptoms of CIDD-induced radiculopathy, myelopathy, and neck pain.

Cervical disc replacement surgery utilizes two types of artificial discs, articulating or non-articulating. The articulating implants are made of two or three solid components arranged in either a ball-in-socket or ball-in-trough configuration (Fakhoury & Dowling, 2022; Shin et al., 2021). The ball-in-trough type more closely resembles the human's natural physiologic translational motion despite the fact that these devices do not have a compressible component that mimics the shock absorbance of the nucleus pulposus in the natural disc (Choi et al., 2017). Articulating devices are also distinguished by the localized ROM they provide to the patient. These distinctions are broken down into constrained, semi-constrained, and unconstrained, which is determined by their ROM being less than, equal to, or greater than physiologic ROM, respectively (Shin et al., 2021). The protheses are typically constructed from cobalt-chrome, polyethylene, stainless steel, or titanium (Goldstein, 2019; Choi et al., 2019).

Constrained CDA designs have fixed or limited center of rotation (COR); the limited mobility results in good stability (Goldstein, 2019; Choi et al., 2019). Semi-constrained designs often have a fixed COR, with some mechanism of paired translation with motion; these devices prevent motion that exceed common physiologic limits and therefore provide moderate stability in instances of excessive motion (Leven et al., 2017; Goldstein, 2019). Unconstrained designs do not have any mechanical restrictions on motion and therefore have dynamic COR (Choi et al., 2019; Wellington et al., 2022). However, the increased mobility results in greater instability (Goldstein, 2019). Additionally, unconstrained replacements may be prone to anterior migration and extrusion out of the disc space due to their ROM being greater than the average physiologic measurements (Shin et al., 2021).

There are currently nine cervical artificial disc protheses approved for use in CDA by the FDA; however, only three are approved for use in two-level CDA (Table 1). All discs have shown non-inferiority, motion preservation, and safety compared to ACDF for the treatment of radiculopathy and motion preservation; however, each CDA's design characteristics and biomaterial properties influence spine kinetics (motions, loads) differently. Each of the cervical disc prostheses reviewed by Chang et al. (2022) exhibited effective outcomes within clinical standards. However, the study was limited due to time on the market and the vast array of options available. As a result, the review did not reveal significant clinical differences between prostheses. Other studies, such as Hui et al. (2019), also showed no short-term differences in clinical or radiological outcomes between patients who received either the M6-C® (Orthofix, Lewisville, TX) or Mobi-C® (Zimmer Biomet/LDR Medical, Warsaw, IN) implants, two of the most widely used prostheses. Hui et al. (2019) also stated that follow-up studies were needed to determine long-term outcomes and that determinations could not be made because the devices are so new in terms of clinical standards.

Though disc replacement surgery has been around since 1966, determining the superiority of brand-specific devices cannot be decided at this time due to the wide variety of choices and the surgical option of the better-known disc fusion over disc replacement. The average number of ACDF surgeries performed in the U.S. each year is approximately 132,000; ACDF surgeries are performed more often than CDA surgeries at a ratio of 18:1 (Saifi et al., 2018). With there being no leading component in the market, it appears that CDA implant device choice is based on the anthropometric needs of the patient and the personal preference of the surgeon (Guyer et al., 2021).

Table 1. List of FDA Approved Artificial Cervical Disc Protheses Used in Cervical Disc Arthroplasty Procedures

Prestige ST®	Medtronic Spine (Memphis, TN)	2007	Constrained	Single
Prodisc-C®	DePuy Synthes: Johnson & Johnson (Raynham, MA)	2007	Semi-constrained	Single
Bryan®	Medtronic Spine (Memphis, TN)	2009	Constrained	Single
Secure-C®	Globus Medical (Audubon, PA)	2012	Semi-constrained	Single
PCM®	NuVasive (San Diego, CA)	2012	Semi-constrained	Single
Mobi-C®	Biomet Zimmer/LDR Medical (Warsaw, IN)	2013	Unconstrained	Single Two
Prestige LP®	Medtronic Spine (Memphis, TN)	2014 2016	Constrained	Single Two
M6-C®	Spinal Kinetics/Orthofix (Sunnyvale, CA/Lewisville, TX)	2019	Unconstrained	Single
Simplify®	NuVasive (San Diego, CA)	2020 2021	Semi-Constrained	Single Two

Note. The information in Table 1 is current as of July of 2022.

A main advantage of CDA over cervical spinal fusion as a CSSIP is the retention of more natural cervical spine biomechanics. An overwhelming amount of research shows greater CROM with CDA as compared to ACDF (Lee et al., 2014; Zou et al., 2017; Lavelle et al., 2019). Specifically, more normal cervical spine kinematics are retained; consequently, a more normal ROM can be preserved. The resulting CROM preservation helps to prevent the onset of ASD. Aside from the negative complications seen with unconstrained devices, the use of constrained and semi-constrained devices has been shown to allow for better ROMs than ACDF (Fakhoury & Dowling, 2022).

Recent publications have reported that CDA outcomes have been similar and, at times, even superior to ACDF (Shin et al., 2021). Reoperation rates following a CSSIP are higher among those receiving ACDF as compared to CDR (Buckland et al., 2016). A common reason for reoperation among patients receiving ACDF is ASD. Surgical complication rates for CDA were as low as 1.5%, with reoperation rates between 1.8% and 5.4%; as compared to ACDF revision rate ranges from 2.1% to 9.13% (Veeravagu et al., 2014). After a long-term five-year follow-up, researchers found that the rate of reoperation for patients who underwent ACDF was five times higher than patients who had a CDA (Delamarter & Ziegler, 2013). At a seven-year follow-up, the reoperation rate for patients with ACDF was 15%.

Despite the positive outcomes described above, CDA could potentially lead to heterotopic ossification (HO), or abnormal bone growth in non-skeletal soft tissues. There is also a risk of implant extrusion or migration. Other potential complications include difficulty swallowing (dysphagia) and implant subsidence into the bone (Liang et al., 2020).

A common complication after CSSIPs that does not significantly affect reoperation is dysphagia, or difficulty swallowing. Dysphagia tends to resolve itself within three months after surgery with low incidence of moderate to severe dysphagia (Rihn et al., 2011). Peng et al. (2022) found that there was no significant difference in dysphagia occurrence between the ACDF and CDA groups at any of the follow-ups. Additionally, the study found that dysphagia had a low incidence rate in the CDA short-term follow-up, which may likely be due to better peri-operative and post-operative care (Peng et al., 2022).

Applicability and Consideration of CSSIPs as CIDD Treatment in Military Aviation Populations

Most medical, post-surgical guidelines regarding CSSIPs are based on general population health, activities, and life expectancy. For civilians, recommendations for return to work are highly variable depending on physician and patient, but also tend to depend on factors such as the physical demand of the work (De Biase et al., 2020). In an online survey sent to the American Association of Neurological Surgeons, most health care providers would allow a patient to return to sedentary work one to two weeks after single-level ACDF (Huntoon et al., 2022). Also, for single-level ACDF, 80.7% of survey respondents would allow full exercise (without contact) after one month (Huntoon et al., 2022). Data outcomes from a study completed by Traynelis et. al (2012) showed that patients who received a CDA returned to work sooner than those that received ACDF. There have also been studies that examined return to play fitness outcomes or guidelines for athletes following CSSIPs (Joaquim et al., 2016; Watkins IV et al., 2018; Leider et al., 2021). However, all aforementioned study outcomes were determined via surveys completed by surgeons or retrospective reviews of medical health records and database sources. Furthermore, operational activities of military aviation environments are more dynamic and physically demanding than general population and athletic environments. As a result, military personnel frequently experience more accelerated CIDD. The harsher operating conditions are likely to have differing effects on CSSIP outcomes in military aviators compared to civilian populations. More information, obtained from lab- and field-based human subject research, is needed to more accurately assess RTD in military aviation environments.

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Military Aviation Operational Environment Characteristics

Vibration in aviation environments can be complex; it is comprised of the internal motion of aircraft parts and the varying external affects associated with air travel or motion (Griffin, 1990; U.S. Department of Defense [DoD], 2019). Rotary-wing aircraft operations create unique dynamic mechanical loadings on aviators. The vibration frequencies in these aircraft, originating from the rotor motion, are lower in comparison to vibrations within fixed-wing aircraft (DoD, 2019). Jet aircraft vibration patterns are dominated by higher frequencies resulting from random external effects; maximum vibrations occur during takeoff and are caused by engine exhaust noise (Griffin, 1990; DoD, 2019). Aviators are continuously and consistently exposed to lengthy periods of sitting (for more than four hours) with awkward postures while experiencing whole-body vibration (WBV) in their operational environments. Poor posture ("helo hunch") has long been identified as a significant contributor to aviator back pain, and seating ergonomics (e.g., minimal or no seat adjustment capabilities) have been cited by pilots as a leading cause of back pain. Additionally, in fighter and tactical jet fixed-wing aviation environments, forces sustained during ejection, landings, and maneuvers can lead to neck pain and injury (Lang et al., 2022).

The cervical spine is held in an upright, neutral position requiring the cervical muscles to apply constant work in addition to compensatory actions to maintain head and neck posture under WBV (Dupuis & Zerlett, 1987). The work of the cervical spine musculature combined with WBV forces results in increased loading on vertebral spinous processes in the lower cervical spine (Dupuis & Zerlett, 1987). The resulting dynamic, mechanical loadings can be intensified on the aircrew, adversely affecting human performance, which can be further exacerbated by helmets and helmet systems.

The military aviation helmet is a multi-functional tool, providing impact protection while also serving as a mounting platform for critical life-support and operational enhancement technologies, such as communication systems, oxygen/gas masks, night vision goggles, and head-up displays. Flight helmet configuration depends on flight platform and mission. HSM is the quantitative description of properties (mass and center of mass [CM] offset) in a system worn on the head and supported by the neck. The presence or wear of HSM increases the loading placed on the musculoskeletal ligamentous neck (muscles, ligaments, discs), which can cause both musculoskeletal fatigue and potential degenerative changes.

Ideal helmets are lightweight and provide a comfortable fit for the mission duration. In addition, all attached components should be balanced relative to the combined head and helmet CM offset. The neck loading is magnified by adding mass and increasing the center CM offset away from the atlanto-occipital complex (AOC), the head's pivot point on the spine. Vertical CM offset (z-axis; above and below) variation is thought to be most critical when considering crash-induced severe neck injury risk; whereas longitudinal CM variation (x-axis; forward and aft) is important when considering wearer fatigue, performance, and chronic musculoskeletal injury (McEntire & Shanahan, 1998). The spinal pain from acute injuries and degeneration in military aviation operational environments can lead to chronic and debilitating effects, even disqualifying some Soldiers from specific duties or continued military service.

Aviator Medical Waiver and Disqualification Guidelines for CSSIPs

For civilian pilots that fall under the Federal Aviation Administration (FAA), there is no clear guidance on returning to flight status after receiving a CSSIP. In the online Guide for Aviation Medical Examiners (2022), the FAA has advised that "a history of intervertebral disc surgery is not disqualifying. If the applicant is asymptomatic, has completely recovered from surgery, is taking no medication, and has suffered no neurological deficit, the Examiner should confirm these facts then issue any class of medical certificate, providing that the individual meets all the medical standards for that class" (p. 150). Without clear guidelines on return to flight (or RTD) CROM values or a directed waiting period, the time for a civilian pilot to return to flight status is up to the individual medical examiner.

According to current U.S. Army Standards of Medical Fitness for flying duty waiver guidelines in Army Regulation (AR) 40-501: 4-18e (DA, 2019):

> Spinal surgery, including, but not limited to, fusion or disc replacement at any level is disqualifying. This is not disqualifying for Class 4 (unmanned aircraft system operators and air traffic controllers) unless there are residual symptoms. Waivers are not considered for Class 1 (applicants for flight training). Disc replacement is limited to two levels for waiver consideration. Fusion at more than two levels is not considered for waiver in Class 2 (uniformed pilots) or 3 (uniformed personnel), except fixed-wing pilots with fusion will be considered on a case by case. (p. 38)

Initial waiver/exception to policy requires that an aeromedical provider complete a musculoskeletal and neurologic examination of CROM, mobility, pain, and sensory/reflex findings, yet no quantitative evidence or guideline exists for fitness RTD waivers for aviators who have undergone a CSSIP. As a result, aviation medical examiners typically follow the USAF and U.S. Navy (USN) recommendations for a post-treatment observation period of six months. The rationale behind the observation period is to allow fusion from an ACDF procedure to occur; this policy has also been adopted for patients who receive CDA (Miller et al., 2018).

For pilots in the USAF, the Aerospace Medicine Waiver Guide (AMWG) February 2022 revision states the following related to cervical spine fusion:

> A history of herniated nucleus pulposus (HNP) or surgery for it is disqualifying for flight class (FC) I/IA/II/III and requires a waiver under Medical Standards Directory (MSD) K6: history of frank HNP or history of surgery or chemonucleolysis for that condition. All flying classes and OSD personnel require a waiver when they fall under MSD K5: "Herniation of nucleus pulposus, when symptoms and associated objective findings are of such a degree as to require repeated hospitalization, significant duty limitations, or frequent absences from duty." MSD K5 is disqualifying for retention standards, so would also require a Medical Evaluation Board (MEB) or Review In Lieu Of (RILO, p. HNP-1).

Additionally, there is a minimum observation period of four months for FC III/ground-based operator (GBO) and six months for FC II (USAF, 2022). In scenarios with over four years of stability, there is no requirement for an Aeromedical Consultation Service (ACS) review. Instead, they are conducted at the waiver authority's discretion. For CDA, the policy states "If surgical intervention is contemplated, note that cervical disc arthroplasties (artificial disc replacements) are not routinely aeromedically-approved for high-performance aircraft operation waiver, and may also be duty-limiting for personnel on jump status" (USAF, 2022, p. HNP-1). There is a minimum six-month post-treatment observation period. Furthermore, CDA waivers are often restricted to non-high-performance aircraft (USAF, 2022).

Pilots in the USN and U.S. Marine Corps (USMC) are both governed under the USN Aeromedical Reference and Waiver Guide (NAMI, 2022). According to the aeromedical reference and waiver guidance by NAMI: "A history of symptomatic HNP with or without surgery is disqualifying. Waivers may be considered on a case-by-case basis" (2022, p. Orthopedics-10). Rotary-wing and ejection seat pilots who receive a single-level fusion, are at least six months post-treatment, are pain-free, and are without radicular symptoms are disqualified and recommended for waiver. Pilots who have undergone a two-level fusion or single-level CDA, are at least six-months post-treatment, are pain free, and are without radicular symptoms are also disqualified and recommended for waiver. However, radiographs must show healing and no flexion or extension instability. Additionally, all waivers are considered on a case-by-case basis for rotary-wing pilots; ejection seat pilots are excluded from obtaining waivers (NAMI, 2022).

Considerations for CDA as a CSSIP in Military Aviation Environments

According to the Aeromedical Electronic Resource Office (AERO) in 2022, cervical spine disease or neck pain was present in the records of 164 waivers issued to U.S. Army aviators in 2021. Of these waivers, 21 waivers and 8 disqualifications were directly attributed to neck pain or cervical spine disease (AERO, 2022). Additionally, there are numerous documented cases of aviators with CSSIPs currently serving on active duty with approved waivers. A data query of 2016 to 2021 records revealed a total of 30 Army aviators with CSSIPs (AERO, 2022). There were 14 aviators who had received ADCF CSSIP and 16 aviators received the CDA CSSIP. In those who had received the ACDF, 10 were waivered while 4 were suspended. In those who have undergone CDA, 13 were waivered and 3 were suspended (AERO, 2022). The mean age for the aviators who had received ACDF was 42.4 years, while aviators who had undergone CDA had a younger mean age (39 years) (AERO, 2022).

While CDA has recently become a more popular CSSIP among U.S. Army aviators, the option of CDA as a CSSIP presents new questions for aviation military populations due to their exposure to unique environments and occupational conditions. In support of U.S. Army modernization efforts for multi-domain operations (MDO), the Future Vertical Lift Cross Functional Team is developing aircraft with greater flight capabilities. These increased flight capabilities (e.g., forward speed) create the potential for greater forces in future helicopter crashes than have previously been experienced. Additionally, little is known about the performance of these CDA devices in the dynamic environment and resulting cervical spine response in high vertical load "G" forces typically seen in rotary-wing crash environments and mishaps. Fuller et. al (2020) presented the first reported occurrence of a traumatic fracture in a patient who had previously undergone CDA. The patient was involved in a motorcycle crash, resulting in a hangman's fracture that was treated with a cervical collar. Following the incident, the prostheses remained intact and there was no evidence of misalignment. Additionally, the literature review by Fuller (2020) of published outcomes suggested that differences in posttrauma complications in CSSIPs (ACDF versus CDA) were attributed to varying locations of maximal stress in the prosthetic devices and implants (Fuller et al., 2020). The prosthetic devices utilized in both types of CSSIPs need to be tested in simulated aviation crash and impact scenarios.

Potential exposures to the occupant differ in the military compared to the civilian environment. Vertical impacts and weapon recoil are just some of the events that U.S. aviators may be exposed to during missions, and variables such as personal protection equipment (PPE) and seating systems may affect the occupant kinematics during the event (Rhodes et al., 2022). Furthermore, an analysis of U.S. Army aviation mishap injury patterns (Shanahan & Shanahan, 1989) revealed a strong relationship between vertical velocity change and spinal injuries. Investigations of CSSIPs prostheses in these dynamic environments should be conducted to ensure they do not contribute to increased spinal injury risk in survivable aviator mishap events. Additionally, these investigations could help determine whether one CSSIP or type of prostheses is better suited for populations who are at a high risk for trauma, such as military aviators. Furthermore, there is minimal information or knowledge regarding long-term health and operational effects in Soldiers with CDA. Therefore, it is difficult, if not impossible, for military researchers to give biomedically valid and empirical data to drive recommendations to policy makers and commanders based on the potential benefits when weighed against potential pitfalls of adopting CDA in lieu of, or complimentary to, ACDF.

The rate of fitness, or RTD occurrence, following a CSSIP has been examined in military populations. A recent study investigating the RTD for military single- and two-level ACDF recipients showed an 88% RTD occurrence rate; the RTD rate was found to be higher in military personnel with a rank of E7 (99%) compared to those at E6 and lower (73%) (Tumialán et al., 2019). An earlier study by Tumialán et al. (2010) reported a shorter RTD timeline of less than or equal to 12 weeks in CDA recipients compared to the literature-based mean RTD time of 16.5 weeks for ACDF recipients. Another study reported a 95% RTD rate in active-duty military with CDA (Kang et al., 2013). However, neither of these studies involved direct comparisons of CDA RTD rates to RTD rates of those with ACDF. A comparison study that evaluated the outcomes of military personnel who had CDA or ACDF CSSIPs reported RTD rates of 93% and 89%, respectively; however, no specifics about military duty status, MOS or operating environments were provided (Tracey et al., 2014). Cleveland et al. (2015) reported that out of 34 military CDA recipients, 28 (82%) returned to duty in 8.5 ± 8.0 weeks; however, no military aviators were within this group. Miller et al. (2018) conducted a retrospective study of active-duty rotary- and fixed-wing pilots from the U.S. Army, U.S. Air Force, and Navy/Marine Corps branches that had undergone a CSSIP. Miller et al. (2018) concluded that RTD for military aviators after CSSIPs appeared to be safe and the most likely outcome for most military aviators. Their analyses ultimately identified an 84.6% RTD rate among military aviators who had a CSSIP with an RTD timeline of 287 days (Miller et al., 2018). Among those pilots, there were two with single-level ACDF and seven with single-level CDA; the others either had a two-level CDA or hybrid construct (Miller et al., 2018). While the RTD rate can be determined based on CSSIP type using the data presented, this information cannot be determined based on type of CDA implant device. In addition to the limitations mentioned within, all study outcomes were also determined via case reports or retrospective reviews of military health records and epidemiology database sources.

Research Gaps and Relevant Current Research Focus Area Efforts

The USAARL's initial investigation and consideration regarding the use and impact of CDA as a CSSIP treatment option in military populations began shortly after the FDA granted approval of the first cervical disc implant, the Prestige ST® (Medtronic Sofamor Danek, Memphis, TN), in 2007. Research and aviation medical examiner personnel at the USAARL held meetings with concerned parties to discuss CDA in the military operational environment and forge a plan to address potential problems and outcomes. Since that time, monumental gains in the advancement and improvement of CDA procedures have occurred. Examples of these CDA advancements include the new development or revamping of old surgical techniques and approaches, artificial disc implant designs, and improved biomaterials used in disc implant fabrication.

Even with the vast advances in CDA procedures and prosthetics over the last decade, significant gaps still remain in the knowledge base regarding the full impact of both CSSIPs in military operating environment. Researchers at the USAARL and the Medical College of Wisconsin/Clement J. Zablocki Veterans Affairs Medical Center (MCW/VAMC) have begun the task of investigating the long-term function and effects following CSSIPs. Recent efforts have involved head-to-head studies with FDA-approved artificial discs and ACDF using the caprine goat animal model, evaluations of civilian and very limited military patient data, and computational models of different CDA and ACDF with a particular focus on the incidence of ASD (Choi et al., 2019; Choi et al., 2020; Purushothaman et al., 2020; Choi et al., 2021a; Purushothaman, Choi et al., 2021; Yoganandan et al., 2021; Srinivasan et al., 2021; Tan et al., 2022).

The outcomes of this work resulted in successful replication of HO using the longitudinal animal model via continual monitoring of the radiological status of the caprine neck and clinical scales of HO scores. Additionally, it was determined that the occurrence of HO depends on the type and design of artificial cervical disc prostheses. Data outcomes have also demonstrated the effects of migration in the animal, confirming a similar phenomenon observed in some civilian CDA patients. Further, FDA-approved artificial discs were simulated in MCW/VAMC's validated computational three-dimensional finite element model (FEM) of the subaxial cervical spine (C3-C7 vertebrae). Using this model, clinical metrics such as the CROM, disc pressures, and facet loads were quantified at the level of interest and adjacent levels. Results showed that these biomedical parameters are nonuniform across different types and designs of artificial discs.

A review of published data from military literatures and from civilian studies showed that performances of CDA are noninferior in both groups, while specific conclusions and recommendations for factors such as RTD for aviator populations with control groups were not addressed. Taken together, conclusions from this work have demonstrated that CDA procedures 1) maintain ROMs at surgical levels, 2) decrease transference of motions and loads on adjacent segments, and 3) appear to be a safe alternative to ACDF and facilitate early RTD. However, this work should be replicated and expanded using post-mortem human subjects (PMHS) to determine human response outcomes for comparison to caprine models, across multiple CDA implant types, after exposure to military aviation operations.

Despite the progress made with our own work, as well as the community, into assessing the performance of artificial discs regarding HO, post-surgical motion, and spinal column load-sharing, these studies were conducted under civilian physiological loadings. Flexion, extension, and axial rotation are common repetitive cervical motions for Soldier populations. Aviation environments use these cervical motions while conducting flight or aircraft maneuvers and tasks. Previous research at the USAARL (Williams et al., 2022a; 2022b) revealed that UH-60 and AH-64 pilots require lower CROM in a typical flight than the maximum values in many general population, non-aviation references. If flight surgeons were to use these non-aviation references in flight fitness or RTD determinations, they could end up grounding aviators that may be fit for flight duties with or without CSSIP. Additionally, cervical spine motions and loadings are impacted by the wear of mission-required HSM. Because cervical spine kinematics are returned to more normal ranges after CDA, it is worth considering, assessing, and evaluating health benefits and operational effectiveness of this CSSIP in military aviation populations. Additionally, assessments should be made to determine whether the ROM advantage provided by CDA is significant or necessary for mission effectiveness or fitness for duty. Human subject volunteer (HSV) studies are needed to address these research gaps.

Some foundational work in military-specific exposures has already been started that will provide tools, methodology, and data for addressing the knowledge gaps identified in this review. For example, additional work by MCW/VAMC has been conducted to determine the effects of HSM on head-neck responses in males and females via validated cervical spine FEM and HSV studies (Choi et al., 2021b; John, Arun et al., 2017; John, Yoganandan et al., 2017; John, Kumar et al., 2018; John et al., 2018a; John et al., 2018b; John et al., 2019; John et al., 2021; Purushothaman, Humm et al., 2021; Purushothaman & Yoganandan, 2022). The use of the FEM allowed the identification of changes due to HSM under different accelerative loading scenarios. Additionally, data outcomes reflected that female spines respond with greater segmental motions than male spines, as well as the fact that motions and loads within the neck segments are level and acceleration vector-dependent. Using upright Magnetic Resonance Images (MRI) collected from civilian young healthy subjects, they successfully quantified spinal morphological variations due to prolonged (a few hours) HSM wear. Additionally, it was demonstrated that the prolonged use of HSM in a normal seated posture alters internal load-paths within the spine via changes to level-specific muscle geometrical factors such as change in centroid radius and angulation with respect to the osteoligamentous column. These changes over time may induce additional stresses within the neuromusculoskeletal structures eliciting neck pain with HSM.

Any changes in muscle and vertebral geometries sustained with the use of HSM and prolonged seated postures in a military aviator seat on a day-to-day basis may advance the process of spinal degradation over time leading to neck pain. Changes in area, centroid, and radius contribute to alterations in the loading pattern of the osteoligamentous column and, over time, may also account for curvature alterations. The significant differences between male and female cervical spine musculoskeletal geometries (or anatomy), with and without CSSIPs, underscore the need to obtain data specific to sex and cervical spine health populations within the civilian and military aviator operational environments.

Conclusion

There has been little to no in vivo and in vitro military-relevant evaluation to determine the long-term impact of CSSIPs. Additionally, the option of CDA as a CSSIP presents new questions for military aviators who are exposed to unique environments and occupational conditions. More quantifiable and operationally relevant data are needed to assess the biomechanical, physiologic, kinematic, operational performance effects and limitations, and injury risk of military populations post-CSSIP, especially within military aviator populations, to determine whether those that have had these interventions are fit for duty.

Military aviation operational environments are unique and complex. As a result, aviators are operating under mentally and physically demanding conditions. Spine-associated symptoms and pathology have a detrimental effect on aviator operational readiness and mission performance. Neck pain and cervical disc degeneration are well documented in military personnel resulting in thousands of lost work hours and significant cost in diagnosing and treating these issues. Experienced aviator retention and endurance are a major concern.

Implementation of CSSIPs, specifically CDA, has the potential for pain mitigation/relief for aviators, ultimately contributing to improved mission effectiveness and extended aviator careers. Preliminary results indicate that fusion recipients still endure pain and loss of ROM, whereas CDA recipients are more likely to be pain-free with greater ROM. Current military aeromedical practice considers both ACDF and CDA as disqualifying. Fusion recipients are frequently given waivers, and CDA is considered for a waiver only on a case-by-case basis because there is uncertainty regarding the option of CDA as a CSSIP in military aviation occupational conditions.

The USAARL conducted a comprehensive literature review to update the state of knowledge on CSSIPs and provide research strategy recommendations necessary to obtain biomedically valid operationally relevant data to update and improve medical guidelines for military fitness for RTD in military aviators following the surgical procedures. A logical continuation of the current efforts is to extend data outcomes, approaches, and assessments from previous literature, database, animal model, and computational model studies towards epidemiological, PMHS, and HSV research studies. The recommendations, with more details and specifics, are provided in a subsequent report: USAARL-TECH-SR--2023-06 (Madison et al., 2022). The resulting study outcomes and improved medical guidelines will allow military personnel to make better informed decisions about their medical needs when considering the potential effects on their careers. Most importantly, the research recommendations and outcomes will address an identified need, not just in Army aviation, but in aviation populations across military branches, both domestic and international, as well as in civilian populations.

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Appendix A. Acronyms and Abbreviations

ACDF	Anterior cervical discectomy fusion
ACDR	Artificial cervical disc replacement
ACS	Aeromedical Consultation Service
AERO	Aeromedical Electronic Resource Office
AFHSB	Armed Forces Health Surveillance Branch
AH-64	Army Apache attack helicopter
ALL	Anterior longitudinal ligament
AMWG	Aerospace Medicine Waiver Guide
AR	Army regulation
ASD	Adjacent segment disease
AT&L	Acquisition, technology, and logistics
BDR	Biodynamics Data Resource
CDA	Cervical disc arthroplasty
CIDD	Cervical spine intervertebral disc disease
COR	Center of rotation
CROM	Cervical range of motion
CSSIP	Cervical spine surgical intervention procedure
DMED	Defense Medical Epidemiology Database
DA	Department of Army
DoD	Department of Defense
DUSD	Deputy Under Secretary of Defense
FAA	Federal Aviation Administration
FC	Flight class
FDA	U.S. Food and Drug Administration
FEM	Finite element model
GBO	Ground based operator
HNP	Herniated nucleus pulposus
HO	Heterotopic ossification
HSM	Head-supported mass
HSV	Human subject volunteer
I&E	Installations and environment
IRCOBI	International Research Council on the Biomechanics of Injury
IVD	Intervertebral discs
MARS	Multi-Axis Ride Simulator
MCW	Medical College of Wisconsin
MDO	Multi-domain operations
MEB	Medical Evaluation Board
MOS	Military occupational specialties
MRI	Magnetic resonance images
MSD	Medical Standards Directory
NAMI	Naval Aerospace Medical Institute
NASS	North American Spine Society
NBDL	Naval Biodynamics Laboratory

OSD	Office of the Secretary of Defense
OUSD	Office of the Under Secretary of Defense
PMHS	Post-mortem human subjects
PPE	Personal protective equipment
RILO	Review in lieu of
RTD	Return to duty
SCI	Spinal cord injury
TAIHOD	Total Army Injury and Health Outcomes Database
UH-60	Army Blackhawk utility helicopter
USAARL	U.S. Army Aeromedical Research Laboratory
USAF	U.S. Air Force
USMC	U.S. Marine Corps
USN	U.S. Navy
VAMC	Clement J. Zablocki Veterans Affairs Medical Center
VAT	Vertical acceleration tower
WBV	Whole-body vibration

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