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# The Potential Use of Pressure Sensors to Measure Intervertebral Loads in an Aviation Environment

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**14. ABSTRACT**
The U.S. Army aviator has been continuously at risk of spinal injuries as a result of mishaps or routine operation of aircraft. These types of injuries are debilitating to both the individual Soldier and the Department of Defense as a whole. Thus, it becomes imperative to limit spinal injuries to prevent these consequences from continuing forward as the Army moves into the Future Vertical Lift (FVL) environment. However, prior to limiting spinal injuries, the mechanisms behind spinal injuries in an aviation environment need to be further investigated. One potential tool, which has been used to investigate spinal injury, is an intervertebral disc (IVD) pressure sensor. Past research studies have used IVD pressure sensors, both in-vivo and in-vitro, to determine the pressures placed on vertebral bodies during various activities. The purpose of the current study is to review relevant literature and studies and to determine if the use of IVD pressure sensors can further document the mechanisms of spinal injury in an aviation environment.

**15. SUBJECT TERMS**
pressure sensor, intervertebral disc, spinal injury, spine, rotary wing, aviation mishap, IBPG

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**Summary**

The U.S. Army aviator has been continuously at risk of spinal injuries as a result of mishaps or routine aircraft operations. These types of injuries are debilitating to both the individual Warfighter and the Department of Defense as a whole. This is because spinal injuries often involve long-term consequences in the form of prolonged treatment, replacement of the Warfighter, and/or long-term medical bills. Thus, it becomes imperative to limit spinal injuries to prevent these outcomes as the U.S. Army moves into the Future Vertical Lift (FVL) environment. However, before spinal injuries can be mitigated further, the mechanisms behind spinal injuries that occur in the aviation environment need to be further investigated.

One tool that has been used to investigate spinal injury is an intervertebral disc (IVD) pressure sensor. Past research studies have used IVD pressure sensors, both in-vivo and in-vitro, to determine the pressures placed on vertebral bodies during various activities. In such cases, the sensors were either surgically implanted into a living subject (animal or human) or placed into cadaveric functional spinal units (FSUs). In the case of a living subject, the sensors measured the pressures resulting from activities of daily living. The studies using cadaveric FSUs typically investigated pressures leading up to failure, which took the form of structural changes in the vertebral bodies or intervertebral discs.

The current report reviews relevant literature and previous studies to determine if data collected from IVD pressure sensors can further document the mechanisms of spinal injury in an aviation environment.

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## Background

This is a special report issued by the United States Army Aeromedical Research Laboratory (USAARL) in support of research for the Army's Future Vertical Lift (FVL) program. The aim of the current study was to evaluate the ability of using miniature pressure sensors to determine forces acting on individual vertebral bodies during experimental testing. Initially, in-house testing was planned as a part of this effort; however, due to limitations in cadaveric specimen acquisition related to the COVID-19 pandemic, no in-house testing was completed. Despite the lack of in-house testing of the pressure sensors, a literature review was conducted to determine how pressure sensors could be used to better inform researchers regarding injuries sustained in an aviation environment. The following report is a result of that effort.

## Introduction

Spinal injuries experienced by Warfighters have been increasing throughout the years (Blair et al., 2012). The types of spinal injuries among Warfighters range from acute to chronic (Knox, 2011; Blair et al., 2012). Instances that can cause these injuries include mishaps, enemy actions, and operational exposures during dismounted, ground mounted, aviation, and airborne environments, such as aircraft crashes, vehicle accidents, blast exposures, gunshot wounds, parachute opening shock and landing fall, vehicle and aircraft vibration and jolt, and other repeated dynamic loadings that produce loading through the spinal column. One particular group of Warfighters who have particularly been subjected to spinal injuries are U.S. Army aircrew members. The biomechanics of the spine and mechanisms of spinal injury need to be extensively studied to better protect aircrew members from spinal injuries.

Understanding the biomechanics of the spine is imperative to identifying key indicators of spinal injury. An integral element of spine mechanics is the intervertebral disc (IVD), which lies between the vertebral bodies (Figure 1). Intervertebral discs contain a nucleus, annulus fibers, and cartilaginous end plates, which, in combination, enable spine motion, disperse weight, absorb stress from impact, and allow passage of nutrients (Frost et al., 2019). A key biomarker in IVD mechanics is IVD pressure (Humzah & Soames, 1988). Past research has theorized that the way in which the nucleus pulposus of the IVD distributes pressure can determine the mechanism by which force is transmitted through the spine (Nachemson, 1960). A better understanding of how force is transmitted to and through the spine could provide insight on how to better mitigate the onset of injury.

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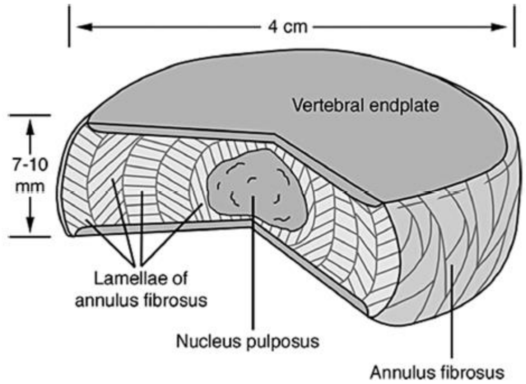


*Figure 1.* An excerpt from Frost et al. (2019) depicting a cut out portion of a normal intervertebral disc with the nucleus pulposus, cartilaginous vertebral endplates, and annulus fibrosus.

One tool that can be used to measure force being transmitted through the spine is a pressure sensor inserted into the IVD. The concept of using pressure sensors in the IVD is not novel, and research using different techniques has been performed for over the past 65 years. However, the use of these sensors to perform military-specific research has not been well documented. The purpose of this special report is to briefly review the history of IVD pressure research, review the types of spinal injuries observed in Warfighters, and discuss the potential benefit of using sensors to study IVD pressure for U.S. Army aviation-specific research.

## Historical Intervertebral Disc Pressure Research

There is a long history of studies aimed at understanding the loading capabilities of the spine. Published literature investigating the compressive loading tolerance of the spine dates back to the 1800s (Rauber, 1876; Messerer, 1880). In 1904, it was theorized that the IVD carried a pressure of its own (Fick, 1904), but it was not until 1953 when measurement of IVD pressure was first published. A study by Naylor and Smare (1953) measured lumbar IVD pressure on an unloaded human spine segment using a mercury-filled needle connected to a Bourdon Gauge (Naylor & Smare, 1953). Naylor and Smare (1953) conducted one of the first studies to document changes in IVD pressure due to environmental changes; they documented increases in IVD pressure due to immersion in a fluid (1953). In another study, Nachemson published one of the earliest conducted in-vivo studies on loaded spine segments, investigating the effect of posture on IVD pressure (Nachemson, 1966). Nachemson's study involved inserting a custom-designed hollow needle with a membrane that covered a lateral opening in the side, into the IVD of a single subject at the lumbar level to measure pressure (Nachemson, 1966). The needle was then connected to a transducer and an amplifier to record pressure values. While the needle was inserted into the subject's lumbar IVD posteriorly at a 45-degree angle, the subject was asked to hold a sitting, standing, and reclined seated position. IVD pressure was recorded for all postures.

The concept of using a pressure-sensing needle has been relatively unchanged since its conception. However, different techniques of insertion and securing methods have been employed based on study goals. The following are examples of the advancements in techniques and technology that have been made since Nachemson (1966). The following is not an exhaustive list of all the research that has been completed. A new technique of securing the needle can be found in Wilke et al. (1999), where a custom belt was designed to allow a pressure-sensing needle to be inserted into a lumbar level IVD and held in place for wirelessly measuring pressure through different activities of daily living. Additionally, the majority of studies have focused on the measurements of the lumbar or lower thoracic intervertebral discs due to needle/sensor size. As technology has improved, researchers have expanded measurements to higher levels of the spine.

Cripton et al. (2001) developed a technique of inserting a sensor into the cervical spine rather than a pressure-measuring needle. This sensor was 1.5 millimeters (mm) in diameter and 0.3 mm in thickness in order to minimize the influence of the sensing device (Cripton et al., 2001). The pressure sensor originated from Precision Measurement Company in Ann Arbor, MI, USA and had a pressure range of 0 to 3.5 megapascal (MPa). The sensor contained a 350 Ω strain gauge that was mounted inside of the pressure sensor. The deformation of the strain gauge was linearly proportional to the pressure acting on the measuring face of the pressure sensor. In the experiment, the strain gauge was connected as the active arm in a Wheatstone bridge circuit. A "three-wire" circuit configuration was used for temperature compensation (Hoffman, 1989). The sensor was calibrated to 1.6 MPa in a pressure chamber, which created a linear relationship between the output voltage from the amplified Wheatstone bridge and the applied pressure. A hollowed out needle was used as the sensor guide tube, which was first inserted into a cadaver's cervical spine ex-vivo, then the sensor was pushed through the guide tube with an insertion wire. Cripton et al. (2001) was able to measure the IVD pressure of axial loaded functional spinal units (FSUs) at several cervical levels, including C4-C5 and C2-C3. The study established that the measured pressure increased linearly with an increase in loading (Cripton et al., 2001). Various researchers (e.g., Dmitriev et al., 2005 and Demetropoulos et al., 2010) have adopted this technique for measuring IVD pressure as described by Cripton et al. (2001).

In the past, there had been concerns with the previous methods of using pressure-sensing needles and inserting pressure-sensing transducers due to the size and rigidity of such tools. As a result, Dennison et al. (2008) developed a technique of inserting a fiber optic cable for the measurement of IVD pressure. The study used Fibre-Bragg grating (FBG) sensors to measure pressure by measuring the Bragg wavelength. If hydrostatic pressure is applied to an FBG sensor, the strains within the fiber optic cable cause the Bragg wavelength to shift. Such shifts vary linearly with applied pressures ranging from 0 to 50 MPa (Xu et al., 1993). In this experiment, the FBG sensors originated from Blue Road Research in Gresham, Oregon, USA and were calibrated for hydrostatic pressure (Dennison et al., 2008). For calibration, the FBG sensors were inserted into a glycerin-charged vessel with a manual pump to influence pressure. The sensor calibration consisted of two protocols, a linearly incremental increase in pressure from 1 MPa to 6.9 MPa, and a hysteresis protocol, where pressure was cycled from 1.4 MPa to 6.9 MPa and then back to 1.4 MPa at 0.1 MPa per second (MPa/s). An optical spectrum analyzer was used to record the Bragg wavelength.

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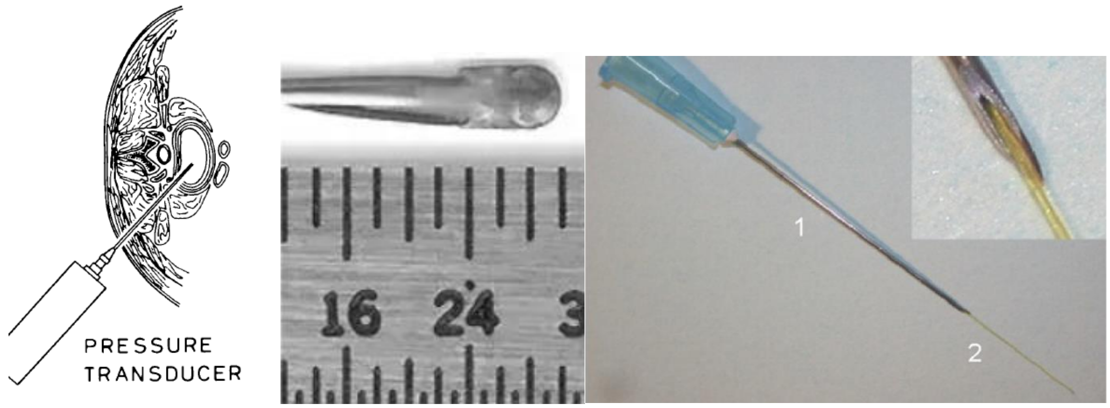
During ex-vivo experimentation, an FBG optic cable that was 125 micrometers in diameter was inserted through a 25-gauge hypodermic needle and inserted into the nucleus pulposus (Dennison et al., 2008). The FBG sensor was pushed through the needle and the needle was retracted to the annulus to shield the cable. It was found that this method produced measurements similar to those reported in other studies, such as Cripton et al. (2001), but was thought to be less disruptive to spine biomechanics due to the reduction of displaced tissue and having a less rigid structure (Figure 2). Other researchers (Roriz et al., 2011; Streijger et al., 2017) have also employed the use of FBG sensors in research involving the measurement of IVD pressure.




(a) (b) (c)

*Figure 2.* (a) An excerpt from Nachemson (1966) displaying the insertion of the needle pressure transducer into the IVD; (b) An image of the miniature pressure sensor developed by Precision Measurement Company (Ann Arbor, MI) that was used by Cripton et al. (2001) to measure IVD pressure; (c) An excerpt from Dennison et al. (2008) displaying the 1) hypodermic needle with the 2) FBG sensor exiting the needle.

**Military Related Spine Injuries**

Spinal injuries have long been a debilitating injury for Service Members. In addition, the spinal injuries observed among military members range from acute to chronic. These types of injuries are not only detrimental to the individual Service Member, but also affect the overall readiness of the Department of Defense. Spinal injuries have long lasting effects that require multiple medical visits, rehabilitation, loss of duty days, and possibly even surgeries, which can lead to restricted (or loss of) duty status. All of these treatment strategies come at a cost to the Department of Defense and the Federal Government through decreased readiness, direct payment for treatment, disability payments, or even the cost of replacing the Service Member.

Acute spinal injuries were found to occur frequently for Warfighters involved in combat. Instances of combat-related spinal injuries have been increasing throughout the years, and the highest rate of occurrence was observed in Operation Iraqi Freedom and Operation Enduring Freedom (Blair et al., 2012). In fact, it was found that thoracolumbar spinal injuries from battle or explosives dramatically increased at the beginning of the Operation Iraqi Freedom in 2003, and decreased thereafter (Medical Surveillance Monthly Report [MSMR], 2012). Although battle-type injuries increased, wounds from transportation accidents and falls were the leading cause of thoracolumbar injury during both Operation Iraqi Freedom and Operation Enduring Freedom (MSMR, 2012). Whether the spinal injury occurs in combat or non-combat settings, there is a great cost to the Department of Defense and the Federal Government for treating, and possibly the loss of, the wounded Warfighters.

One particular group of the military that has been shown to be subjected to both acute and chronic spinal injuries is that of Army aviation (Brozoski et al., 2020; Kelley, 2017). Injuries to aviators come at a large cost to the Department of Defense, as an estimated $9 million is required for replacing an aviator (Gebicke, 1999). The routine occupational hazards of the U.S. Army aviator place them at increased risk of sustaining spinal injuries (Belmont et al., 2001). It has been shown that acute spinal injuries occur because of the high accelerative loading experienced from rotorcraft ground impact (Shanahan & Mastroianni, 1984; Shanahan & Shanahan, 1989). A review of rotorcraft mishaps from 1990 to 2014 was performed to detail the frequency and vertebral level of resulting spinal injuries (Brozoski et al., 2020). It was found that spinal injuries resulting from rotorcraft mishaps predominately affected the thoracolumbar region, and remained consistent with previous studies observing the time period of 1975 to 1985 (Brozoski et al., 2020; Shanahan & Shanahan, 1989). Overall, the acute spinal injuries of U.S. Army aviators, including thoracolumbar fractures, were noted to be caused by high-energy axial loadings, such as those that occur during helicopter mishaps (Belmont et al., 2001).

Additionally, recent research found that helicopter pilots were the leading occupational group with the strongest correlation between time in a seated position and incidence of lower back pain, amongst occupations that remained seated for greater than half of working time (Lis et al., 2007). Although generally not attributed to a combat injury, lower back pain is frequently observed among helicopter pilots, and can often prevent Warfighters from being able to perform on the battlefield (Cunningham et al., 2010; Kelley et al., 2017; Knox et al., 2011; Orsello et al., 2013). Lower back pain has been a problem for Service Members for many years and has been identified as a risk factor for Warfighters to be medically discharged from the military (Benedict et al., 2019). Furthermore, the U.S. Army was found to have the highest rate of lower back pain when compared to other military branches (Knox et al., 2011). Attributing to the high incidence rate, lower back pain has been reported among several occupational specialties throughout the Army, such as members of the infantry as well as other rotorcraft aircrew (Knox et al., 2011; Kelley et al., 2017). Lower back pain among U.S. Army aircrew members could stem from degenerative changes at the lumbar joints. A high incidence of herniated nucleus pulposis are known to occur among military helicopter pilots (Orsello et al., 2013; Mason et al., 1996; Raggatt, 2000). Research has theorized and correlations have been made that propose disc degeneration as a possible contributor to lower back pain (Luoma et al., 2000). Interestingly, IVD pressure has been found, by Sato et al. (1999), to be an indicator of disc degeneration.

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## Potential Benefit of IVD Pressure Research in the Military

The modern Warfighter has a wide range of possible exposures that could lead to spinal injury. In order to better understand these injuries and determine possible injury mechanisms, the biomechanics of the spine need to be extensively studied. With this knowledge, new strategies can be introduced to protect the Warfighter. The IVD is a structure that plays a large role in the overall spinal mechanics. A key biomarker in IVD mechanics is IVD pressure (Humzah & Soames, 1988). Studying IVD mechanics during spinal loading could provide insight on the mechanism of injury and spinal loading patterns among the Warfighter population. A possible device that can be used to study the mechanical properties of the IVD in environments applicable to the Warfighter population are pressure sensors.

In previous studies, lower back pain has been identified as a frequent injury among Warfighters, including U.S. Army aviators (Cunningham et al., 2010; Kelley et al., 2017). It has also been identified that the onset of lower back pain during military service is an indicator of future lower back pain (Mattila et al., 2017). Heavy spinal loading over a person's lifetime from occupational exposures has been associated with an increase in disc degeneration (Battié et al., 1995), and disc degeneration has been associated with lower back pain (Luoma et al., 2000). U.S. Army aviators are often required to operate with increased loads to carry necessary items (e.g., armor, helmet, survival vests) required for combat missions and survival (Kelley et al., 2017; Nevin & Means, 2009). These increased loads could promote disc degeneration and the onset for lower back pain. Additionally, lower back pain is a common symptom among U.S. Army aircrew members due to repetitive whole body vibrations, maladaptive posture, and inadequate lumbar support in aircraft seating, amongst other factors (De Oliveira & Nadal, 2005; Kåsin et al., 2011; Kelley et al., 2017). As IVD pressure has been identified as an indicator of disc degeneration (Sato et al., 1999), the use of pressure sensors could offer insight on the likelihood of lower back pain development. Furthermore, the typical upper body load that a Warfighter experiences could be measured at the IVD level using pressure sensors. With the insertion of sensors into cadaveric IVDs, an internal measurement of the load that the spine experiences can be made at multiple levels during a simulated aviation environment or event.

Mechanisms of acute spinal injury in the military range from blasts, gunshot wounds, motor vehicle accidents, and rotary aircraft mishaps. The use of IVD pressure sensors offers a way of measuring the body's response to such trauma. Research has advanced in this area and the potential to damage internal structures has been reduced due to the technological advancement of IVD pressure sensors. These advancements limit the drawbacks of using pressure sensors in both cadaveric and animal models. Through the combination of cadaveric or animal models, the trauma that Warfighters experience in combat or non-combat can be re-created and studied. Pressure sensors inserted into the IVDs can provide real-time measurement of how load is transferred through the spine. The use of IVD pressure sensors could be crucial to understanding spine trauma from rotary aircraft mishaps. More work is required to establish injury assessment reference values for spinal injuries occurring in rotary aircraft. Traditional work on spinal trauma has been focused on civilian accidents, such as car crashes, that do not compare to the magnitude and direction of loading that occurs from a rotary-wing aircraft mishap. Previous research has already identified that spinal injury patterns resulting from rotary-wing aircraft mishaps differ from what has been observed in traditional civilian motor vehicle accidents (Yoganandan et al., 2015). Furthermore, injuries to the spine caused by rotary-wing mishaps have been observed to occur in all levels of the spine: cervical, thoracic, and lumbar (Brozoski et al., 2020). It is not only imperative to perform high accelerative testing at magnitudes that reflect aircraft mishap loading, but to also focus the outcome measurements on spine biomechanics. Combining the use of pressure sensors in cadaveric IVDs during high accelerative testing could offer a unique insight to trauma-specific spine biomechanics. A better understanding of spinal load transfer will also help identify injury thresholds that can be used to inform the U.S. Army's FVL program regarding design criteria for the development of novel aircraft with improved flight characteristics and tactical capabilities.

## Conclusions

Research regarding the measurement of IVD pressure goes back over 60 years. The process of measuring IVD pressure through placement of a sensor inside the IVD has remained similar throughout history. What has changed the most, however, is that the technology employed to perform such research has evolved from the use of needles to the insertion of small pressure sensors and fiber optic wire. Although many studies have used different technologies, the goals have not changed substantially over the years. All of these diverse technologies have been used to gain more knowledge about the properties of IVD pressure and spine biomechanics.

One important gap in the literature is the application of IVD pressure research within military medical research. It has been demonstrated through the search of existing literature that spinal injuries are a frequent occurrence for U.S. Army aircrew members and further investigations to address these issues are required. A potential tool that could aid in this research is the use of pressure sensors inserted into the IVD. Issues regarding both acute and chronic spinal injuries can be investigated through the study of IVD pressure. These injuries can be investigated within several research areas, including human subjects, animal models, validation of computational models, or cadaveric component testing. The use of IVD pressure sensors in the various research areas would have limitations that need to be addressed by the researcher. However, insights gained from this research could direct changes in military tactics, techniques, and procedures (TTPs), training, and combat operations, as well as inform design of personal protective equipment and future rotorcraft vehicles.

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