applied sciences

IMPACT FACTOR 2.5

CITESCORE 5.5

Article

Human Cervical Intervertebral Disc Pressure Response During Non-Injurious Quasistatic Motion: A Feasibility Study

Sara Sochor, Jesús R. Jiménez Octavio, Carlos J. Carpintero Rubio, Mark R. Sochor, Juan M. Asensio-Gil, Carlos Rodríguez-Morcillo García and Francisco J. Lopez-Valdes

Special Issue
Biomechanics and Ergonomics in Prevention of Injuries

Edited by
Dr. Jesus Ramon Jimenez-Octavio and Dr. Corina Klug

MDPI

https://doi.org/10.3390/app15116167

applied sciences

Article

Human Cervical Intervertebral Disc Pressure Response During Non-Injurious Quasistatic Motion: A Feasibility Study

Sara Sochor [1,*], Jesús R. Jiménez Octavio [1], Carlos J. Carpintero Rubio [1], Mark R. Sochor [2], Juan M. Asensio-Gil [1], Carlos Rodríguez-Morcillo García [1] and Francisco J. Lopez-Valdes [1]

[1] MOBIOS Lab, Institute for Research in Technology, Comillas Pontifical University, C. de Santa Cruz de Marcenado, 26, 28015 Madrid, Spain; joctavio@comillas.edu (J.R.J.O.); ccarpintero@comillas.edu (C.J.C.R.); jasensio@comillas.edu (J.M.A.-G.); carlos.rodriguez@comillas.edu (C.R.-M.G.); fjlvaldes@comillas.edu (F.J.L.-V.)

[2] Center for Applied Biomechanics, Department of Mechanical and Aerospace Engineering, University of Virginia, 4040 Lewis and Clark Dr., Charlottesville, VA 22911, USA; ms7ha@uvahealth.org

* Correspondence: sara.sochor@alu.comillas.edu

Featured Application: This study presents a novel approach to measuring cervical spine intradiscal pressure using a minimally invasive sensor in a whole-body post-mortem human subject (PMHS, i.e., cadaver). The timing, rate, and magnitude of disc loading provided by this sensor are highly significant to gaining insight into cervical spine mechanics during head/neck motion.

Abstract: The human neck is highly vulnerable in motor vehicle crashes, and cervical spine response data are essential to improve injury prediction tools (e.g., crash test dummies, human body models). This feasibility study aimed to implement the use of pressure sensors in whole-body post-mortem human subject (PMHS) cervical spine intervertebral discs (IVDs) to confirm the feasibility and repeatability of cervical IVD pressure response to biomechanic research. Two fresh frozen whole-body PMHSs were instrumented with miniature pressure sensors (Model 060S, Precision Measurement Company, Ann Arbor, MI, USA) at three cervical IVD levels (C3/C4, C5/C6, and C7/T1) using minimally invasive surgical insertion techniques. Each PMHS underwent three quasistatic motion test trials, and each trial included multiple head/neck motions (i.e., gentle traction, flexion/extension, lateral bending, axial rotation, and forced tension/compression). Results showed marked pressure differences between both the cervical level assessed and the motion undertaken as well as successful intra-subject repeatability between the three motion trials. This study demonstrates that changes in cervical IVD pressure are associated with motion events of the cervical spine. Cervical IVD response data could be utilized to assess and supplement the characterization of the head/neck complex motion, and data could facilitate the continued improvement of injury prediction tools.

Keywords: biomechanics; cervical spine; neck; intervertebral disc; cadaver; whole body; PMHS; pressure; injury prevention; non-injurious

check for updates

Academic Editor: Francesco Cappello

Received: 28 April 2025
Revised: 21 May 2025
Accepted: 27 May 2025
Published: 30 May 2025

Citation: Sochor, S.; Jiménez Octavio, J.R.; Carpintero Rubio, C.J.; Sochor, M.R.; Asensio-Gil, J.M.; Rodríguez- Morcillo García, C.; Lopez-Valdes, F.J. Human Cervical Intervertebral Disc Pressure Response During Non-Injurious Quasistatic Motion: A Feasibility Study. *Appl. Sci.* **2025**, *15*, 6167. https://doi.org/10.3390/app15116167

1. Introduction

Motor vehicle-related incidents are the 12th leading cause of death on a global level, resulting in ~1.19 million fatalities annually [1]. Road traffic injuries remain the primary cause of death for children and young people aged five to 29 years, and two-thirds of all road traffic fatalities occur among people of working age (18–59 years) [2]. An additional

~20 to 50 million more people suffer non-fatal motor vehicle-related injuries, many incurring a long-term disability [2]. The cervical spine is a crucial, albeit vulnerable link between the head and torso. It is highly susceptible to acute injury in motor vehicle crashes due to both its positioning between the mass of the head and the mass/restraint of the torso, and relatively limited support compared to these adjacent anatomical structures. Motor vehicle collisions are a leading cause of acute spine and spinal cord injuries in both Spain and the United States [3–7]. Estimates suggest that some form of cervical injury occurs in ~50–70% of all motor vehicle crash-related injuries and in ~20–25% of motor vehicle fatalities [8–11].

Traumatic cervical spine injuries can range from mild whiplash to severe conditions like spinal cord damage, which may lead to paralysis or other permanent impairments [7,12]. The frequency of motor vehicle-related cervical spine injuries has been found to be inversely proportional to the severity [10]. The most common type of crash-related cervical spine injuries are whiplash-associated disorders (WADs), i.e., non-specific soft tissue injuries/musculoligamentous strains; though, these injuries are the least serious clinically. More severe cervical spine injuries (e.g., vertebral fractures/dislocations, disc injuries, and/or spinal cord injuries) are less common but still quite significant [3]. Estimates suggest that around 1–2% of occupants in motor vehicle crashes may experience serious (Abbreviated Injury Scale [13], AIS 3+) cervical spine injuries [3,10], and these numbers may be subject to underestimation due to pre-admission mortality rates of 25–40% [11,14]. The percentages vary greatly depending on factors such as the severity of the crash, the demographics of the injured individuals, and injury severity; still, the National Spinal Cord Injury (SCI) Statistical Center reports an incidence of approximately 18,000 new traumatic SCI patients per year, and more than half of them are cervical SCI [6]. Understanding serious/severe (i.e., AIS 3+) traumatic cervical spine injuries resulting from motor vehicle incidents is crucial due to their potential for severe, long-term consequences.

Cervical spine injuries are a notable concern in motor vehicle collisions, and ongoing advancements in vehicle safety technology and injury prediction and prevention tools continue to play a crucial role in reducing their prevalence and severity. Human surrogates for injury biomechanic testing must closely mimic human physical characteristics (i.e., anthropometry, tissue response, and injury thresholds) so that the surrogate mechanical responses simulate corresponding human responses when exposed to analogous experimental conditions [5,15]. Two of the most used human surrogates in injury biomechanic research are anthropometric test devices (ATDs, i.e., "crash test dummies") and computational models (i.e., finite element (FE) and human body models (HBMs)). Both of these surrogates exhibit a distinct set of intrinsic advantages and disadvantages [16–19]; however, the actual human body tolerance falls somewhere between the investigative capacities of both ATDs and the FE/HBM. This limitation highlights the importance and necessity of PMHS experimentation to better define the response of human tissues and to ultimately ensure that the surrogates are valid. The assessment of cervical spine injury potential in biomechanic research, especially using PMHSs, is highly valuable to the field.

There is a paucity of data for cervical IVD tissue response, and there are positive implications for understanding IVD response as it relates to overall cervical spine kinematics, especially for more widespread application to injury biomechanics. Cervical IVD tissue response data could be utilized to assess and supplement the characterization of the head/neck complex motion, and data could facilitate the continued improvement of injury prediction tools (ATDs and HMBs) [20,21]. Previous studies have attempted to establish a relationship between IVD pressures and cervical spine motion/loading [22–27]; however, to date, the exact relationship of cervical IVD pressures to loading is still uncertain and remains the focus of this research.

Many research initiatives have made efforts to evaluate PMHS head and cervical spine kinematics [5,8,28–37], yet there has not been a robust attempt to characterize the biomechanical response of cervical IVDs due to anatomical and kinematic limitations for instrumentation. Access to the cervical spine IVDs is extremely limited due to the requirement for an anterior surgical approach, the small size of the cervical spine, and impediments created by surrounding anatomical structures (notably the mandible and thorax). The extreme and multi-directional head/neck motions enabled by the cervical spine itself ultimately limit instrumentation visibility and viability during motion (i.e., instrumentation often negatively interacts with the chin/chest). Previous experimental options for assessing spinal loads in a PMHS involved the invasive implantation of multi-axis load cell instrumentation (i.e., replacing an IVD or vertebral body with a load cell) to directly measure the load path. This method is less than ideal, as it disrupts the integrity of the primary and surrounding anatomical structures and negatively and artificially affects the overall PMHS kinematics/kinetics [38]. A more favourable option for quantifying cervical spine injury potential is to measure loads indirectly through the IVD pressure, which has been correlated to axial spine loading [39,40]. Investigating IVD pressure measurements using miniature pressure sensors preserves anatomical and structural spine integrity while providing biomechanical response data necessary to quantify injurious insults to the spine.

In this study, we investigated the potential feasibility of cervical IVD pressure sensors in performing biomechanical research. We hypothesized that a relationship between IVD pressures and cervical spine loading exists, and cervical spine motion is correlated with changes in cervical IVD pressure; thus, the goal of this study was to capture cervical IVD pressure responses during quasistatic motion of the head and neck. Cervical IVD tissue response data could be utilized to assess and supplement the characterization of the head/neck complex motion during both non-injurious quasistatic motion testing as well as during dynamic injurious experimentation, and data could facilitate the continued improvement of injury prediction tools.

2. Materials and Methods

Two fresh frozen whole-body PMHSs (one male, one female) were procured according to the procedures established at MOBIOS Lab and received approval from the Universidad Pontificia Comillas Ethics Committee (Dictamen 2022/37). All experimental procedures were performed according to the principles outlined in the Declaration of Helsinki (1975, revised in 2013), national regulations in Spain, and in accordance with the ethical guidelines established by the Human Usage Review Panel of the US National Highway Traffic Safety Administration (NHTSA). PMHSs were pre-screened for bloodborne pathogens and handled using universal precautions per laboratory safety guidelines. Demographic and anthropometric information (i.e., sex, age, height, weight, and cause of death) was collected for each PMHS (Table 1), and medical histories/computed tomography (CT) images were reviewed to rule out anatomical anomalies, prior surgical intervention/hardware, and/or evidence of spine disease/pathology. Subjects were deemed to have healthy cervical vertebrae and intervertebral discs with limited (age-appropriate) degeneration. PMHSs were preserved frozen at ~$-20°$ C until needed and thawed for ~24 h at room temperature prior to instrumentation and subsequent testing.

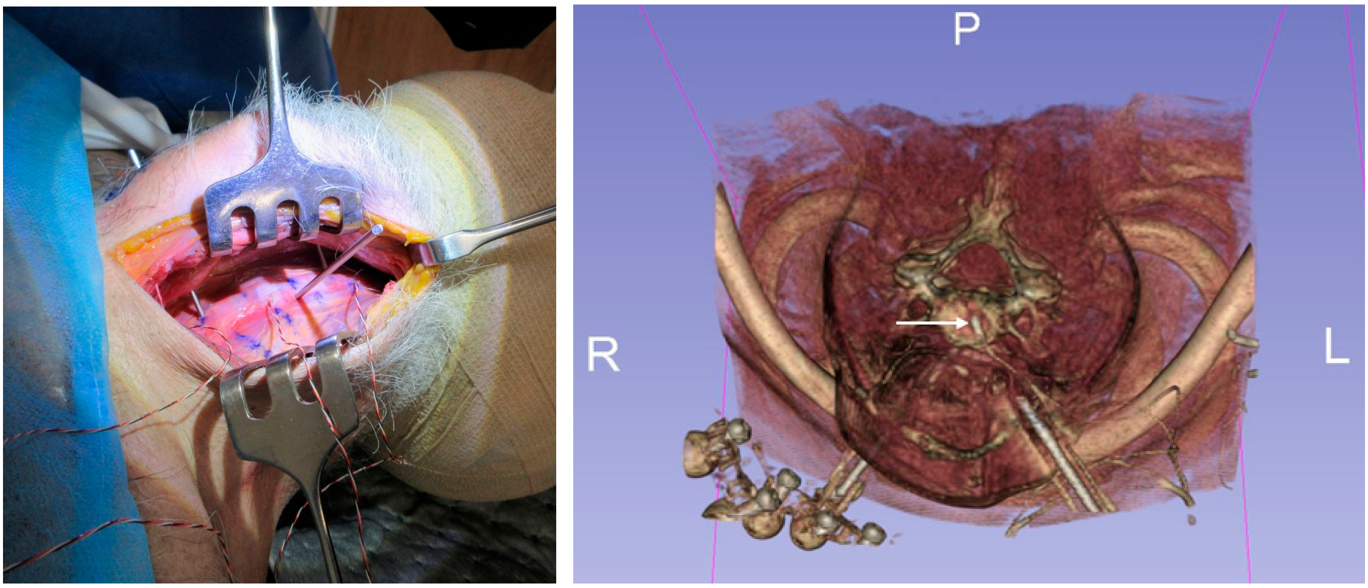
Cervical spine instrumentation for data capture requires specialized surgical techniques and miniature-scale data acquisition tools to provide practical data due to dynamic anatomical space limitations. Miniature pressure sensors (Model 060S, range 0–500 psi, Precision Measurement Company, Ann Arbor, MI, USA) were chosen for the proposed experimentation for their small size (3.0 mm length $\times$ 1.5 mm width $\times$ 0.3 mm thickness) and ability to withstand the post-mortem soft tissue environment. This pressure transducer was previously used to record cervical spine disc pressures in PMHS functional spinal units (FSUs) by Cripton et al. [25] and others in a more clinical/surgical setting [26,41–50]. Prior to sensor use, a plausibility check was conducted to confirm pressure sensor calibration linearity.

Table 1. PMHS demographics and head/neck anthropometry.

PMHS #	MOBIOS Donor ID	Sex	Age [yr]	Stature [cm]	Mass [kg]	Cause of Death
1	0028M	Male	65	153.5	53.2	Metastatic Lung Cancer
2	0027F	Female	53	155.0	49.8	Leukemia
Head/Neck Anthropometry [cm]					**PMHS 1**	**PMHS 2**
Head Circumference					55.6	55.5
Head Length					18.2	18.5
Head Breadth					14.5	14.5
Head Height					22.5	23.5
Neck Circumference					36.0	33.0

To our knowledge, placing pressure sensors into whole-body PMHS cervical spine IVDs has not been previously reported in the biomechanic literature, and, to accomplish this, we developed novel and specialized instrumentation techniques. The PMHSs were instrumented with miniature pressure sensors at three cervical IVD levels (C3/C4, C5/C6, and C7/T1) using a minimally invasive surgical technique for IVD pressure sensor insertion in which no internal soft tissue anatomical structures were removed and/or damaged during the instrumentation process (Figure 1). Three-dimensional motion tracking arrays with reflective spherical markers were installed at three cervical vertebral levels (C4, C5, and C7) and the skull, and a six degree-of-freedom (i.e., triaxial accelerometer + triaxial angular rate) sensor package (6DX PRO-A 500G, DTS, Seal Beach, CA, USA) was installed on the skull to measure head/neck angular displacement (Figure 2). Additional surface markers provided supplemental anatomical landmarks for 3D tracking analysis. PMHSs underwent two computed tomography (CT) scans (0.625 mm slice thickness and 0.625 mm slice interval), one prior to specimen preparation and then again after specimens were instrumented/tested. The initial CT scan was used to confirm the absence of pre-existing anatomical anomaly/injury and to determine specimen-specific anatomy to plan for pressure sensor insertion point/depth as reported in Burns et al. [38]. The second scan confirmed the instrumentation position/pressure sensor location within the cervical IVD.

Three non-injurious quasistatic motion test trials were performed for each PMHS, and each trial included multiple head/neck motions (gentle traction, flexion/extension, left/right lateral bending, left/right axial rotation, and forced tension/compression) (Figure 3). The PMHS was positioned on a rigid seat in a “natural” upright seated position (~25° recline posterior torso angle). The PMHS torso was firmly secured to the seat back to prevent upper body motion, which facilitated independent motion of the head/neck complex during manual manipulation. Pressure sensors were zeroed with the specimen in the “neutral” position (i.e., Frankfurt horizontal plane) at test onset. Head/neck motions were manually performed by a licenced physiotherapist based on approximate normal ranges of motion (ROMs) for the joints of the human craniocervical region. For each of the head/neck motions, the physiotherapist moved the PMHS head and neck from the “neutral” position to the maximum motion range and then back to the “neutral” position, at a predefined quasistatic speed. Care was taken not to exceed physiological/anatomical maximums and to limit motion in other planes. The clinically “safe” maximums of each motion were implemented to avoid iatrogenic injury and/or interaction issues between the head and the installed instrumentation.



(**a**) (**b**)

Figure 1. (**a**) Minimally invasive surgical technique for IVD pressure sensor insertion (**b**) and exemplar miniature pressure sensor location (sensor denoted by arrow) in the C5/C6 IVD for PMHS 1 (P = posterior, R = right, L = left).

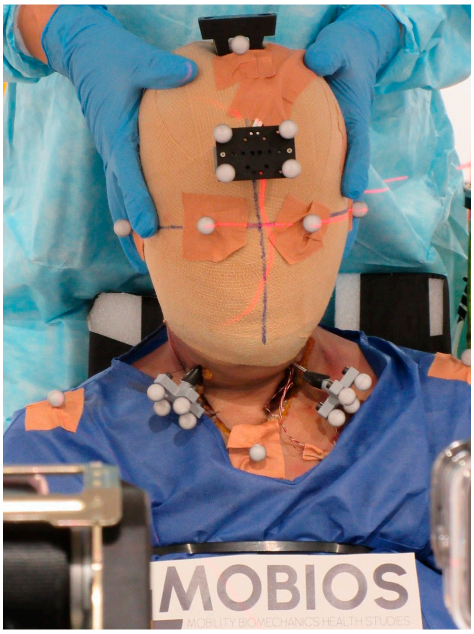
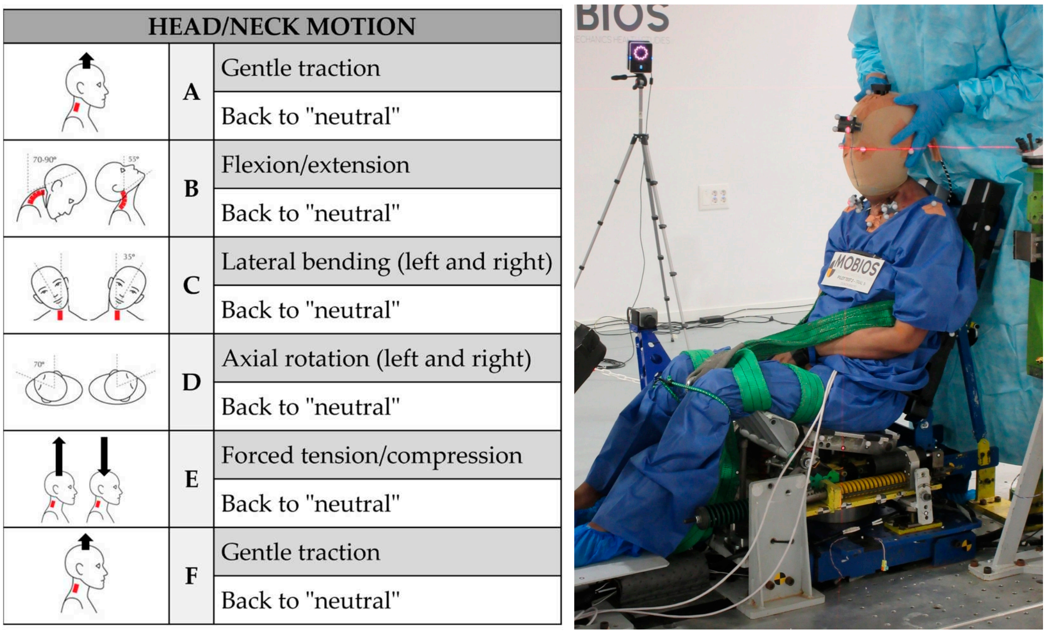


Figure 2. Experimental PMHS cervical spine instrumentation utilizing whole-body PMHS with 3D motion tracking arrays and miniature pressure sensor instrumentation.

Kinematic and pressure data were coordinated and acquired at a sample rate of 100 Hz and 10,000 Hz, respectively. A computer-based nine-channel digital data acquisition system (DTS Slice Micro with DTS DataPRO software version 4.0.752, USA) recorded data from the accelerometer and pressure sensors, and a 3D motion capture system (Vicon Motion System, UK) recorded kinematics. Data analysis was performed in MatLab (MATLAB Version: 9.14.0 (R2023A)).



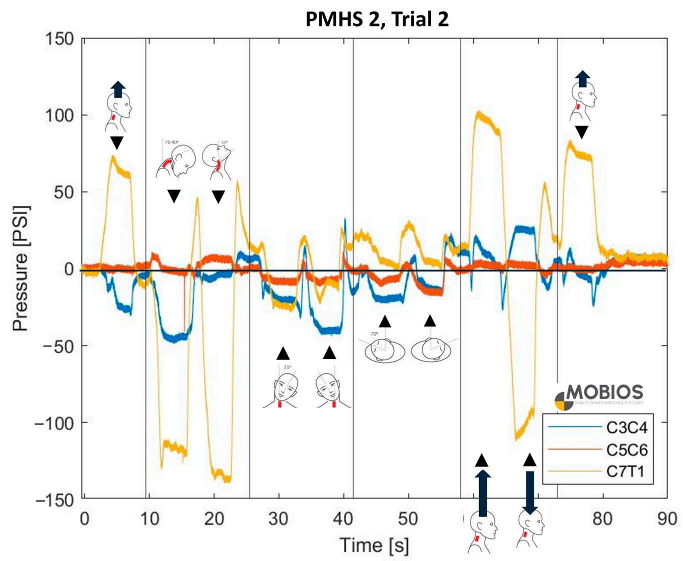
(**a**) (**b**)

Figure 3. (**a**) Three non-injurious quasistatic motion test trials are performed for each PMHS, and each trial includes multiple head/neck motions. (**b**) Head/neck motions are manually performed by a licenced physiotherapist based on approximate normal ranges of motion for the joints of the human craniocervical region.

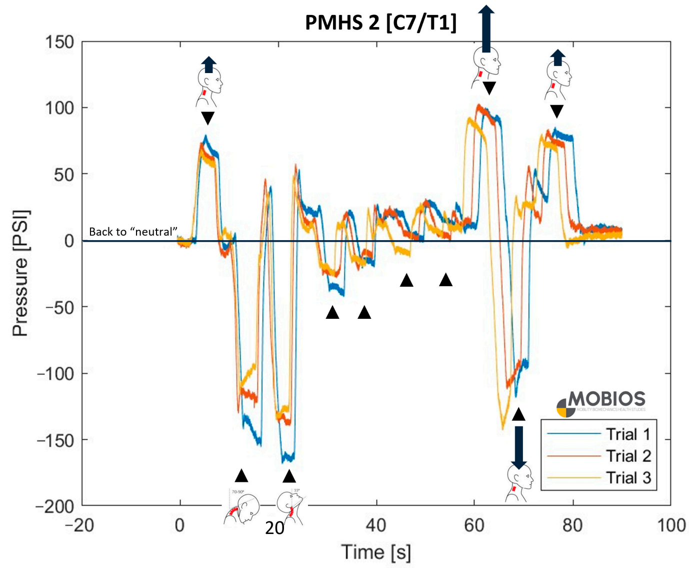
3. Results

Cervical IVD pressure readings were successfully obtained for all three instrumented cervical levels in all three motion trials for both PMHSs. For each subject, results showed marked IVD pressure differences between both the cervical level assessed and the motion undertaken, as well as successful repeatability between the three motion trials (Figure 4). Symmetrical pressure behaviour was noted between analogous motions (i.e., flexion/extension, bilateral lateral bending and axial rotation, and forced tension/compression). Consistent differences in pressure responses were noted between the three instrumented cervical IVD levels. The lowest cervical disc level (C7/T1) exhibited pressure values three times that of both the highest (C3/C4) and middle (C5/C6) disc levels, which were more comparable (Figure 5).

A summary of mean absolute pressure values for all trials for both specimens is reported in Table 2 (full data set is available in Table A1). The average cervical IVD pressure in the gentle traction position was 42.53 +/− 11.83 PSI, and both the beginning and ending gentle traction positions showed comparable peaks. Maximum overall pressures were recorded in the C7-T1 discs, with flexion resulting in the highest pressure (165.71 +/− 44.53 PSI), extension the next highest pressure readings (135.96 +/− 16.75 PSI), followed by forced compression (115.84 +/− 12.37 PSI). More commensurate pressure values were recorded in the C3-C4 and C5-C6 discs (average across all motions 25.85 +/− 8.73 PSI and 24.36 +/− 20.52 PSI, respectively), and these pressures were much lower than those recorded at C7-T1 (average across all motions 74.08 +/− 13.27 PSI) (Figure 5).



(**a**)



(**b**)

Figure 4. Experimental data showing (**a**) cervical IVD pressure readings are successfully obtained for all three cervical IVD levels [C3/C4, C5/C6, and C7/T1] for PMHS 2 during motion trial 2 with (**b**) successful repeatability at each disc level between the three motion trials [e.g., C7/T1 disc level repeatability for PMHS 2].

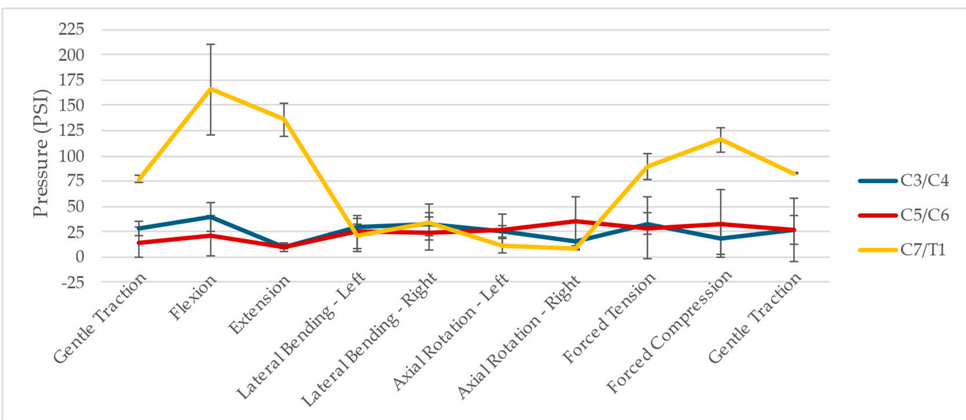


Figure 5. Average absolute value IVD pressure readings for each cervical disc level for each motion.

Table 2. Summary of mean absolute pressure values (PSI) for all trials for both specimens.

	C3/C4		C5/C6		C7/T1	
Motion	**Mean**	**+/−**	**Mean**	**+/−**	**Mean**	**+/−**
Gentle Traction	28.01	6.53	14.22	14.62	76.93	3.86
Flexion	39.47	14.82	21.24	19.80	165.71	44.53
Extension	9.99	4.30	10.20	1.99	135.96	16.75
Lateral Bending—Left	29.42	3.16	24.71	16.74	21.49	16.05
Lateral Bending—Right	32.77	11.62	23.32	16.67	34.07	17.84
Axial Rotation—Left	25.15	5.62	26.31	15.58	10.42	7.21
Axial Rotation—Right	15.84	1.05	35.45	24.08	8.23	0.40
Forced Tension	32.83	10.60	28.52	31.00	89.59	12.80
Forced Compression	18.38	15.96	32.75	33.28	115.84	12.37
Gentle Traction	26.61	13.62	26.85	31.39	82.54	0.94

4. Discussion

We feel that we successfully met our research goal of confirming the feasibility and repeatability of quantifying cervical IVD pressure in physiological motions of the cervical spine. To our knowledge, this is the first study to implement the use of miniature pressure sensors in whole-body PMHS cervical spine IVDs to assess pressure changes during non-injurious quasistatic cervical motion for biomechanical response. The initial analysis of our data showed promising parallels to the two most relevant data sets related to the cervical IVD pressure response reported in the literature [23,24]. Our cervical IVD pressure results show similar trends and comparable pressure values to those reported in the literature despite previous studies involving different specimen/subject types (e.g., FSUs and/or component cervical PMHS spines versus whole-body PMHS as used in this study), investigating varying cervical IVD levels, utilizing specimens with documented clinical cervical disc disease [23] and employing differing pressure sensor instrumentation. The similarity of values reported in the literature from research involving live human patients [23] and component PMHSs [24] suggests that the PMHS is indeed a viable and beneficial surrogate [16,51], and the selected pressure sensor is appropriate for this type of biomechanical experimentation.

We recognize that there were notable differences between the previously reported pressure response values and those obtained in this study; however, as this was a feasibility study, our primary goal was to ensure that the pressure sensors were able to detect and capture changes in cervical IVD pressure. Our secondary goal was to evaluate if our methodology and instrumentation (which differed substantially from many of the previous studies) proffered pressure values that were within the realm of previously reported values. PMHS results from the current feasibility study were closely aligned to previously established pressure ranges (often within a range of approximately +/−1 SD) (Tables 3 and 4).

Hattori [23] provided the first in vivo cervical disc pressure measurements for neutral and non-neutral head/neck positions and established positionally/motion-related cervical IVD pressures in normal/abnormal discs. An important distinction between the Hattori study and the current study is the sample type and size. The Hattori study included 80 cervical IVDs (5% C3/C4, 23% C4/C5, 45% C5/C6, and 28% C6/C7) from 48 pre-operative live patients. Only half of the Hattori cervical IVD levels were directly comparable to those included in this study (levels C3/C4 and C5/C6), while the other IVD levels (C4/C5, C6/C7) were anatomically close but not directly comparable. Additionally, and perhaps most importantly, Hattori did not report pressure values specific to the instrumented IVD level, only average values for each motion; therefore, it is unknown if each value included pressure response values for all disc levels. Hattori's values were also not reported with standard deviations, making comparisons of pressure value ranges difficult. As a result, we averaged our IVD level values in an attempt to best compare the data sets. The lowest instrumented IVD level from our feasibility study (i.e., C7/T1) exhibited the most comparable values (in neutral/gentle traction and in extension), while the average of all three IVD level values were most comparable to Hattori's value in flexion.

Table 3. Comparison of previously established pressure ranges from prior research involving live human patients [23] and results of this study. Pressure values are expressed in PSI.

	SOCHOR, et al. (2024)				HATTORI (1981) [23]
Motion	**AVERAGE**	**C3/C4**	**C5/C6**	**C7/T1**	
Neutral/Gentle Traction	42.53 +/− 11.83	27.31 +/− 10.08	20.53 +/− 23.01	79.74 +/− 2.40	63.58 +/− 7.40
Extension	52.05 +/− 7.68	9.99 +/− 4.30	10.20 +/− 1.99	135.96 +/− 16.75	~132.28
Flexion	75.47 +/− 26.38	39.47 +/− 14.82	21.24 +/− 19.80	165.71 +/− 44.53	~85.34

Table 4. Comparison of previously established pressure ranges from prior research involving component PMHS without muscle force simulation [24] and the averaged results of this study. Pressure values are expressed in PSI.

Level	Motion	POSPIECH (1999) [24]	SOCHOR, et al. (2024)
C3/C4	Flexion/Extension	46.41	24.73 +/− 9.56
	Lateral Bending	23.21	31.09 +/− 7.39
	Axial Rotation	36.26	20.49 +/− 3.33
Level	**Motion**	**POSPIECH (1999) [24]**	**SOCHOR, et al. (2024)**
C5/C6	Flexion/Extension	33.36	15.72 +/− 10.90
	Lateral Bending	23.21	24.01 +/− 16.71
	Axial Rotation	24.66	30.88 +/− 19.83

Static cervical intradiscal pressures are not well documented in the literature, and many intra- and interpersonal anatomical differences exist that affect cervical disc properties (e.g., direct correlations between the extent of cervical disc degeneration and IVD pressure response [22–24]). This phenomenon is well documented in the lumbar spine discs, in which the effects of ageing, including disc degeneration, fibrosis, and/or desiccation, were found to affect/reduce recorded IVD pressures [39,52,53]. Similar effects can be anticipated to occur in the cervical spine. The patients included in the Hattori study presented with clinical "complications", (e.g., cervical spondylotic radiculopathy, disc degeneration and/or herniation, neck trauma, etc.). These diagnoses surely affected the reported pressure responses; however, the degree of negative impact was not quantified. Due to the metallic nature of both the pressure sensors and additional instrumentation for 3D motion capture, CT was deemed the most appropriate and safe method of medical imaging for this feasibility study. We maximized the available medical imaging capabilities (i.e., pre-instrumentation CT) and used applicable portions of other MRI-based cervical IVD grading systems (e.g., Matsumoto's [54], Miyazaki's [55], Jacobs' [56], and Suzuki's [57]) like vertebral endplate changes, narrowing of the disc space/disc height, and the degree of osteophyte formation to "grade" the level of degeneration from CT scans. Cervical intervertebral disc grading often involves evaluating morphological changes and degeneration on dissection [58]. In this feasibility study, post-test autopsy was not amenable to the goal of maximizing the anatomical gift for future experiments; however, plans for future studies do include post-test autopsy to assess disc morphology and clinically grade the level of disc degeneration. Despite these limitations, our results suggest that obtaining cervical IVD pressure readings is possible, even in mature PMHSs.

Pospiech et al. [24] was the first to measure IVD pressure in the cervical spine in an in vitro/experimental setting and sought to establish normal values for cervical IVD pressures under "physiological conditions" with and without simulated muscle forces. Data obtained from intact (pre-discectomy) component cadaveric specimens (C2–C7) sans muscle force simulation were reported as median values and ranges. Trends in pressure response during motion were similar to our data set in that higher pressure values were reported for flexion/extension in comparison with axial rotation and lateral bending. Converse to our results, higher pressures were obtained in the upper segment (C3/C4) than in the lower segment (C5/C6) for flexion/extension and axial rotation. There are certain limitations associated with component PMHSs (i.e., FSUs and component head/neck specimens), as the procurement of these specimen types often disrupts the integrity of the primary and surrounding anatomical structures, negatively and potentially artificially affecting the overall PMHS kinematics/kinetics [21,59]. In the Pospiech et al. study, both the cranial- and caudal-most vertebrae were potted in polymethylmethacrylate and affixed to the test device, which differed greatly from our use of whole-body PMHSs and motion methodology and could have potentially affected the reported pressures. We feel that employing the use of pressure sensors in a whole-body PMHS provided a more realistic head/complex response that we hoped would act as a firm experimental base for our feasibility study.

Previous in vitro and in vivo cervical IVD studies also noted marked interindividual differences in pressure readings between experimental positions/motions [23,24,26,27]; while our two study subjects displayed relatively similarly trended pressure values, there was some variability between the subjects, confirming interindividual differences and suggesting that subject-specific postural configurations (e.g., cervical sagittal balance) and/or subject sex differences may play a role in results [60]. Continued analysis of the 3D motion tracking data from this study is anticipated to provide additional information on subject-specific kinematics and pressure responses. It is also a well-known phenomenon that sex differences exist in both cervical anatomy and biomechanical response (e.g., anatomically, males typically exhibit larger neck cross-sectional area/musculature than females, males are typically stronger than females in both neck flexor and extensor strengths, females typically display a greater neck range of motion than males, and females exhibit lower average neck loads at failure than do males [8,61,62]). Generally, the differences in cervical IVD pressure response between males and females may be affected by simple anatomical differences in which the cervical IVDs in females are smaller than males and thus result in higher IVD pressure readings, an outcome that could be attributed to the principle that disc pressure for a given force is inversely proportional to disc cross-sectional area [63]. As this was a feasibility study, our primary goal was to ensure that the pressure sensors were able to capture changes in cervical IVD pressure during head/neck motion. Our study included one male and one female PMHS; however, given the small sample size of this feasibility study, we are not proposing that the reported pressure values are representative of the whole population, nor are we able to attribute legitimate differences in cervical IVD pressure responses between the sexes.

IVD pressure sensors are capable of recording pressure that can be correlated to load, especially under compressive loading conditions [25,39]. The pressure sensors in this study were zeroed with the specimen in the "neutral" position at test commencement (i.e., Frankfurt horizontal plane parallel to the ground with relatively little external support) to represent an "authentic" anatomical posture with the neck supporting the weight of the head. This methodology was chosen to more equally distribute the resultant IVD responses; however, this approach resulted in measuring pressure relative to this neutral position. In pure tension/compression, the subsequent cervical IVD pressure values are relatively easy to appreciate and interpret; though, in flexion/extension motions, pressure values may depend more heavily on the exact position of the sensor in the cervical IVD. It is possible that regional areas of differing and/or opposing force are created within the disc during neck flexion/extension motions (e.g., neck flexion could result in transitory compression forces in the anterior portion of the disc while also creating contralateral tension forces in the posterior disc, and vice versa for neck extension). Pressure sensor placement in a location of the disc experiencing these regional and opposing forces during specific neck motions may explain the adverse IVD pressures as these changes in disc shape could create areas of vacuum within the disc that could read as negative pressures. Both positive and negative pressure values were recorded for many of the motion trials; therefore, the gauge pressures were examined as relative pressures, and results were examined in terms of absolute value to facilitate data comparison with the existing literature.

This study employed the use of manually applied forces to generate head/neck motions and, despite being performed by a physiotherapist, may have affected the repeatability and/or magnitude of the IVD pressure response. The applied cranio-cervical kinematic intervention pursued two primary objectives: (1) to achieve the maximum physiological range of motion and (2) to respect the individual movement limits of each PMHS. We considered manual cranio-cervical mobilization to be an appropriate method for the aims of our study, as it allowed us to tailor the range of motion to the specific characteristics of each PMHS, including age, tissue stiffness, degenerative changes, and postural configurations [62]. The assessment of joint motion limits, or "articular end-feel", is a standard procedure in physiotherapy and is routinely applied in clinical settings [64]. For this reason, a PhD physiotherapist with extensive expertise in musculoskeletal practice was selected to perform the mobilizations. Throughout the entire battery of tested movements, particular attention was paid to avoid cranio-cervical axial compression during mobilizations, except in trials specifically designed to assess compressive loading. We believe that, under these conditions, the loads transmitted through the intervertebral discs were primarily related to the progressive reduction in slack in capsuloligamentous and myofascial tissues, rather than to externally applied manual axial pressure.

It is important to note that, while similar data trends existed between the two PMHSs, this feasibility study's small sample size, paired with continued refinement of the manually induced quasistatic motions throughout the six test trials (three trials per PMHS), most likely affected the results. Marked improvements in both motion timing and head/neck ROM repeatability were noted to occur as the test series progressed. As a result, any large variations noted between the pressure values of the PMHSs may be attributed to this progressive improvement in test methodology. Additionally, the pressure sensor at the C5/C6 level in PMHS 2 was erroneously/manually displaced and replaced between the first and second motion trials, which could have affected the resulting pressure data and is the most likely reason behind the larger standard deviations noted at this IVD level.

Limitations were observed in this feasibility study. PMHS anatomy and the degree of natural disc degeneration inherent with ageing within the population also greatly affect the potential for ideal sensor placement, as well as the tissue characteristics of the discs themselves [52]. Previous whole-body and component PMHS studies have shown that lumbar IVD pressure data successfully detected changes in loading condition; however, the load signal magnitude and resultant pressure data were deemed to be highly sensitive to the positioning/location of the pressure gauge within the disc [38,52]. The fluid behaviour of the nucleus pulposus yielded improved pressure response data as compared to that from the solid material behaviour exhibited by the annulus fibrosis. Given the extremely small size of the cervical IVD (~15 mm diameter, ~5 mm anterior thickness [65]), perfect placement of the sensor in the centre of the nucleus pulposus proved difficult (Figure 6). Variations in sensor positioning within the three anatomical planes may have affected the recorded pressure outputs.

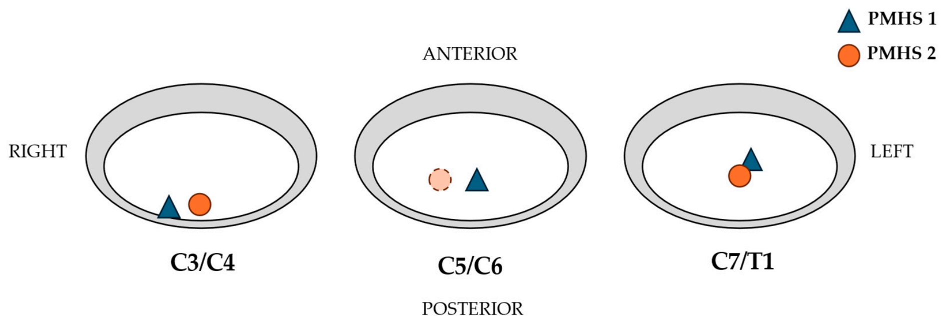


Figure 6. Pressure sensor placement within the cervical IVDs' transverse plane, locations approximated from CT scan imaging. The outer shaded contour represents the approximate area of the cervical disc annulus fibrosis, and the inner contour represents the approximate area of the cervical disc nucleus pulposus. For PMHS 2, the pressure sensor at the C5/C6 level is known to be erroneously/manually displaced and replaced multiple times between the motion trials. The estimated initial sensor position at the C5/C6 level for PMHS 2 is represented by the dashed line.

The nucleus pulposus, at the IVD centre, is composed of a homogeneous semi-fluid/gelatinous matrix and has been found to act hydrostatically. While sensor orientation should be of no consequence for a truly hydrostatically responsive tissue, rotational orientation of the pressure sensor within the cervical IVD may have affected the recorded pressure. Attempts were made to orient the pressure sensors with the active measuring face perpendicular to the vertical IVD axis, and, while the high resolution of our CT images (i.e., 0.625 mm slice interval and thickness) made it possible to locate the sensor location within the three anatomical planes of the cervical IVD, the resolution was not sufficient to confirm its degree of axial rotation. The pressure sensors utilized in this study have one active measuring face and one inactive face; however, per the manufacturer, the direction of the measuring face is unimportant when utilized in a static fluid material (e.g., the hydrostatic nucleus pulposus), as the pressure gradients over the miniature pressure sensor are reported to be negligible. While it is possible that the sensors rotated within the cervical IVD after initial placement, sensor wires were strain relieved to surrounding anatomical structures to mitigate any sensor movement during the motion trials; thus, no shift in sensor location (nor pressure response) was anticipated.

In addition to variation in sensor placement, discrepancies in pressure sensor outputs may be related to basic anatomy. The head/neck complex can be viewed in a simplified manner as a column with a fixed base (i.e., the neck attachment to the torso). In normal cervical motion, there is a greater degree of motion in the upper portion of the cervical spine than in the lower, and there is independent motion/variability between the individual intervertebral levels due to the segmented nature of the spine. As a result of the lower cervical spine attachment to the torso via the ribcage, the lower cervical spine is more rigid, and motion is more structurally arrested. This increase in arrested motion plus the weight of the head and upper cervical spine may result in increased restraining forces, correlating with increased cervical IVD pressure in the lower cervical spine as compared to the higher instrumented disc levels [21,59]. Interestingly, data for the pressure response for other neck tissues/areas (i.e., intrathecal cerebrospinal fluid) show similar responses with greater peak pressure and pressure impulses in lower cervical levels than in higher cervical levels for certain motion events [66]. The cervical spine is overall lordotic but does exhibit a slightly S-shape, especially under compression [8]. The natural kyphotic to lordotic transition in cervical curvature could account for the seemingly lower pressure responses in the mid-cervical spine ~C5/6 (at the point of transition) and higher values in the lower spine.

Lastly, as with any cadaveric-based study, the lack of active neck musculature in the PMHS may be viewed as a primary limitation; however, the stabilization and energy absorption provided by neck muscles was mitigated by establishing a "neutral" plane and position in/to which the head/neck complex was physically manipulated and returned between motions. Range of motion has been previously shown to be similar for both passive and active motion configurations, with the exception of flexion [67]. Quasistatic motion was implemented to validate our new methods and to evaluate the data in a controlled environment. While the effects of absent active musculature may be more pronounced in this quasistatic feasibility study, future research plans include a more dynamic test environment in which the PMHS cervical spine is subjected to dynamic impact forces. Previous dynamic PMHS testing has shown that concerns related to the lack of active musculature are mitigated due to the timing of injury as it relates to muscle reflex timing. For example, Foust et al. reported neck muscle reflex times to be about 50–65 ms for human volunteers exposed to head loading [61], which are considerably longer than the 5–18 ms required to produce cervical spine injury in compressive head impacts as reported by Nightingale et al. [8,29]. Thus, future work will be more aligned with current injury mitigation research and may better quantify the effects of forces on the human head/neck complex and the resultant injuries sustained in such dynamic environments.

Safety research and resultant advancements in vehicle safety technology and injury prevention continue to play a crucial role in reducing the prevalence and severity of cervical spine injuries over time. Assessing human cervical spine kinematics and subsequent injuries resulting from motor vehicle incidents is vital for assessing the broader public health impact. Recognizing the frequency and severity of these injuries helps policymakers and healthcare professionals allocate resources appropriately to inform advancements in vehicle design and safety features. Ongoing research into cervical spine injuries in motor vehicle incidents contributes to the development of innovative safety technologies and crash prevention systems, injury countermeasures, and the design of proper human surrogates for testing. This research could potentially enhance the overall safety of vehicles and roadways.

5. Conclusions

This feasibility study successfully implemented the use of pressure sensors in whole-body PMHS cervical spine IVDs and demonstrated that changes in cervical IVD pressure are associated with motion events of the cervical spine. Results confirm the feasibility and repeatability of cervical IVD pressure response for biomechanic research, and the information provided has the potential for improving our understanding of cervical spine loading. While still limited in terms of validating cervical IVD pressure responses, the recorded values provide useful information regarding the disc pressure rate of increase, the timing of pressure rises, and peak pressure relative to quasistatic cervical motions. Ongoing research into cervical spine injuries in motor vehicle incidents contributes to the development of innovative safety technologies and crash prevention systems, injury countermeasures, and the design of proper human surrogates (i.e., ATDs/HMBs). The results of this feasibility study provide the groundwork for determining the potential applicability of cervical IVD pressures to assess the injury tolerance of the cervical spine.

Author Contributions: Conceptualization, S.S. and F.J.L.-V.; methodology, S.S., C.J.C.R., J.R.J.O. and F.J.L.-V.; software, J.M.A.-G. and C.R.-M.G.; validation, S.S. and J.R.J.O.; formal analysis, S.S. and F.J.L.-V.; investigation, S.S., C.J.C.R., J.R.J.O., J.M.A.-G., C.R.-M.G., M.R.S. and F.J.L.-V.; resources, J.R.J.O., C.R.-M.G. and F.J.L.-V.; data curation, J.M.A.-G. and C.R.-M.G.; writing—original draft preparation, S.S.; writing—review

and editing, S.S., J.R.J.O., J.M.A.-G., C.J.C.R., M.R.S. and F.J.L.-V.; visualization, S.S. and F.J.L.-V.; supervision, S.S., J.R.J.O., C.J.C.R., M.R.S. and F.J.L.-V.; project administration, J.R.J.O. and F.J.L.-V.; funding acquisition, J.R.J.O. and F.J.L.-V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out with MOBIOS Lab, Institute for Research in Technology, Comillas Pontifical University resources. The work was supported by the call "Financiación Proyectos de Investigación Propios 2024" of the University, under the name "Assessment of Neck Loads in Head/Neck Motions within the Physiological Range". The views expressed here are solely those corresponding to the authors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the corresponding author upon request.

Acknowledgments: We would like to acknowledge all personnel at the MOBIOS Lab/Comillas Pontifical University who provided their assistance and expertise in the execution and analysis of this investigation, Brandon Perry for providing data analysis support and, ultimately, for the altruistic gift of donor bodies, without which our research would not be possible.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summary of pressure values (expressed in PSI) for each of the two PMHSs for each of the three non-injurious quasistatic motion test trials.

	PMHS 1, Trial 1			PMHS 1, Trial 2			PMHS 1, Trial 3		
Motion	**C3/C4**	**C5/C6**	**C7/T1**	**C3/C4**	**C5/C6**	**C7/T1**	**C3/C4**	**C5/C6**	**C7/T1**
Gentle Traction	37.62	30.29	79.87	30.95	23.96	78.76	29.32	19.42	80.35
Flexion	29.60	35.87	−213.05	23.61	28.86	−249.71	33.77	41.00	−128.83
Extension	16.03	13.40	−135.64	−15.28	−3.81	−114.75	−7.79	17.61	−121.95
Lateral Bending—Left	35.68	39.68	−21.73	24.78	19.04	−7.24	34.48	50.92	1.44
Lateral Bending—Right	40.13	40.93	59.07	0.39	−9.24	61.56	33.13	55.15	19.43
Axial Rotation—Left	33.88	37.69	−16.29	22.28	14.88	−20.91	31.20	59.41	−9.36
Axial Rotation—Right	42.99	57.11	−18.82	−2.70	33.00	−3.26	4.05	67.34	1.78
Forced Tension	47.75	65.03	72.10	30.88	33.81	81.26	42.35	52.48	88.26
Forced Compression	−3.59	62.51	−132.98	−13.20	59.80	−126.73	−4.49	46.53	−61.58
Gentle Traction	40.79	51.16	68.85	29.81	31.85	87.30	38.12	64.12	89.49
	PMHS 2, Trial 1			**PMHS 2, Trial 2**			**PMHS 2, Trial 3**		
Motion	**C3/C4**	**C5/C6**	**C7/T1**	**C3/C4**	**C5/C6**	**C7/T1**	**C3/C4**	**C5/C6**	**C7/T1**
Gentle Traction	6.61	2.35	79.57	−30.69	−3.85	74.04	−32.88	−5.43	68.98
Flexion	−48.54	−9.26	−155.68	−48.90	−5.14	−130.28	−52.40	7.32	−116.70
Extension	−7.01	8.28	−168.37	−9.22	9.65	−139.59	−4.63	8.45	−135.46
Lateral Bending—Left	−28.96	−15.93	−42.55	−23.05	−11.52	−28.46	−29.54	−11.17	−27.50
Lateral Bending—Right	−39.39	−13.08	−21.15	−43.83	−11.61	−23.04	−39.72	−9.90	−20.19
Axial Rotation—Left	−22.88	−17.87	−1.60	−22.64	−11.90	−1.32	−18.00	−16.10	−13.05
Axial Rotation—Right	−16.33	−22.17	23.15	−16.84	−18.16	−1.39	−12.12	−14.94	1.00
Forced Tension	22.20	5.55	99.97	22.34	6.30	103.00	31.48	7.95	92.94
Forced Compression	24.82	12.90	−118.48	28.29	6.66	−112.27	35.88	8.09	−143.02
Gentle Traction	14.85	−4.35	85.49	13.87	−3.60	83.81	22.22	5.99	80.32

References

1. World Health Organization. *Global Status Report on Road Safety 2023*; World Health Organization: Geneva, Switzerland, 2023.
2. Road Traffic Injuries. Available online: https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries (accessed on 15 October 2024).
3. Kent, R.; Cormier, J.; McMurry, T.L.; Johan Ivarsson, B.; Funk, J.; Hartka, T.; Sochor, M. Spinal injury rates and specific causation in motor vehicle collisions. *Accid. Anal. Prev.* **2023**, *186*, 107047. [CrossRef] [PubMed]

4. Looby, S.; Flanders, A. Spine Trauma. *Radiol. Clin.* **2011**, *49*, 129–163. [CrossRef] [PubMed]
5. Yoganandan, N.; Nahum, A.M.; Melvin, J.W.; The Medical College of Wisconsin Inc on behalf of Narayan Yoganandan (Eds.) *Accidental Injury: Biomechanics and Prevention*; Springer: New York, NY, USA, 2015. [CrossRef]
6. National Spinal Cord Injury Statistical Center. *The 2023 Annual Statistical Report (Complete Public Version) for the Spinal Cord Injury Model Systems*; National Spinal Cord Injury Statistical Center, University of Alabama at Birmingham: Birmingham, AL, USA, 2023.
7. Barriga-Martín, A.; Pérez-Ruiz, P.; Muñoz-Rodríguez, J.R.; Romero-Muñoz, L.; Peral-Alarma, M.; Ríos-León, M.; Álvarez-Bautista, E. Epidemiology of traumatic spinal cord injury in Spain: A ten-year analysis of trend of clinical and demographic characteristics. *J. Spinal Cord Med.* **2024**, 1–7. [CrossRef] [PubMed]
8. Nightingale, R.W.; McElhaney, J.H.; Camacho, D.L.; Kleinberger, M.; Winkelstein, B.A.; Myers, B.S. The Dynamic Responses of the Cervical Spine: Buckling, End Conditions, and Tolerance in Compressive Impacts. *SAE Trans.* **1997**, *106*, 3968–3988.
9. Yoganandan, N.; Haffner, M.; Maiman, D.J.; Nichols, H.; Pintar, F.A.; Jentzen, J.; Weinshel, S.S.; Larson, S.J.; Sances, A. Epidemiology and Injury Biomechanics of Motor Vehicle Related Trauma to the Human Spine. *SAE Trans.* **1989**, *98*, 1790–1809.
10. Freeman, M.D.; Leith, W.M. Estimating the number of traffic crash-related cervical spine injuries in the United States; An analysis and comparison of national crash and hospital data. *Accid. Anal. Prev.* **2020**, *142*, 105571. [CrossRef] [PubMed]
11. Prasad, V.; Schwartz, A.; Bhutani, R.; Sharkey, P.; Schwartz, M. Characteristics of injuries to the cervical spine and spinal cord in polytrauma patient population: Experience from a regional trauma unit. *Spinal Cord* **1999**, *37*, 560–568. [CrossRef]
12. Stein, D.M.; Kufera, J.A.; Ho, S.M.; Ryb, G.E.; Dischinger, P.C.; O'Connor, J.V.; Scalea, T.M. Occupant and crash characteristics for case occupants with cervical spine injuries sustained in motor vehicle collisions. *J. Trauma* **2011**, *70*, 299–309. [CrossRef]
13. Association for the Advancement of Automotive Medicine. *The Abbreviated Injury Scale*; 2015 Revision; AAAM: Des Plaines, IL, USA, 2016.
14. Hadley, M.N.; Sonntag, V.K.H.; Grahm, T.W.; Masferrer, R.; Browner, C. Axis Fractures Resulting from Motor Vehicle Accidents: The Need for Occupant Restraints. *Spine* **1986**, *11*, 861–864. [CrossRef]
15. Mertz, H.J. Anthropomorphic Test Devices. In *Accidental Injury: Biomechanics and Prevention*; Nahum, A.M., Melvin, J.W., Eds.; Springer: New York, NY, USA, 2002; pp. 72–88. [CrossRef]
16. Crandall, J.R.; Bose, D.; Forman, J.; Untaroiu, C.D.; Arregui-Dalmases, C.; Shaw, C.G.; Kerrigan, J.R. Human surrogates for injury biomechanics research. *Clin. Anat.* **2011**, *24*, 362–371. [CrossRef]
17. Iraeus, J.; Poojary, Y.; Jaber, L.; John, J.; Davidsson, J. A new open-source finite element lumbar spine model, its tuning and validation, and development of a tissue-based injury risk function for compression fractures. In Proceedings of the 2023 International Research Council on the Biomechanics of Injury, IRCOBI 2023, Cambridge, UK, 13–15 September 2023. Available online: https://www.ircobi.org/wordpress/downloads/irc23/pdf-files/23132.pdf (accessed on 26 May 2025).
18. Tushak, S.; Bollapragada, V.; O'Cain, C.; Shin, J.; Gepner, B.; Pipkorn, B.; Kerrigan, J. Sensitivity of GHBMC Lumbar Spine Biomechanical Response to Subject-specific Geometric Morphing and Soft Tissue Material Property Scaling. In Proceedings of the 2024 International Research Council on the Biomechanics of Injury, IRCOBI 2024, Stockholm, Sweden, 11–13 September 2024.
19. Yang, K.H. *Basic Finite Element Method as Applied to Injury Biomechanics*; Elsevier: Amsterdam, The Netherlands, 2018. [CrossRef]
20. DeWit, J.A.; Cronin, D.S. Cervical spine segment finite element model for traumatic injury prediction. *J. Mech. Behav. Biomed. Mater.* **2012**, *10*, 138–150. [CrossRef]
21. Morgan, M.I.; Corrales, M.A.; Kaur, H.; Cripton, P.A.; Cronin, D.S. Importance of Neck Boundary Condition and Posture on Cervical Spine Response Assessed using a Detailed Finite Element Human Model in a Head-First Impact. *Ann. Biomed. Eng.* **2025**, 1–13. [CrossRef] [PubMed]
22. Kambin, P.; Abda, S.; Kurpicki, F. Intradiskal Pressure and Volume Recording: Evaluation of Normal and Abnormal Cervical Disks. *Clin. Orthop. Relat. Res. (1976–2007)* **1980**, *146*, 144. [CrossRef]
23. Hattori, S.; Oda, H.; Kawaii, S. Cervical intradiscal pressure in movements and traction of the cervical spine. *Z Orthop.* **1981**, *119*, 568–569.
24. Pospiech, J.; Stolke, D.; Wilke, H.J.; Claes, L.E. Intradiscal pressure recordings in the cervical spine. *Neurosurgery* **1999**, *44*, 379–384; discussion 384–385. [CrossRef]
25. Cripton, P.A.; Dumas, G.A.; Nolte, L.-P. A minimally disruptive technique for measuring intervertebral disc pressure in vitro: Application to the cervical spine. *J. Biomech.* **2001**, *34*, 545–549. [CrossRef]
26. Gudavalli, M.R.; Potluri, T.; Carandang, G.; Havey, R.M.; Voronov, L.I.; Cox, J.M.; Rowell, R.M.; Kruse, R.A.; Joachim, G.C.; Patwardhan, A.G.; et al. Intradiscal Pressure Changes during Manual Cervical Distraction: A Cadaveric Study. *Evid. Based Complement. Alternat. Med.* **2013**, *2013*, 954134. [CrossRef]
27. James, C.M.; Brismée, J.-M.; St-Pierre, M.-O.; Descarreaux, M.; Hooper, T.L.; Nougarou, F.; Bélanger, E.M.; Sobczak, S. Variability of Intradiscal Pressure During Cervical Spine Posterior-Anterior Mobilization: A Cadaveric Investigation. *J. Manip. Physiol. Ther.* **2022**, *45*, 522–530. [CrossRef] [PubMed]
28. Nightingale, R.W. The Dynamics of Head and Cervical Spine Impact. Ph.D. Thesis, Department of Biomedical Engineering Duke University, Durham, NC, USA, 1993.

29. Nightingale, R.W.; McElhaney, J.H.; Richardson, W.J.; Best, T.M.; Myers, B.S. Experimental Impact Injury to the Cervical Spine: Relating Motion of the Head and the Mechanism of Injury. *J. Bone Jt. Surg.* **1996**, *78*, 412–421. [CrossRef]
30. Huelke, D.F.; Mendelsohn, R.A.; States, J.D.; Melvin, J.W. Cervical Fractures and Fracture-dislocations Sustained without Head Impact. *J. Trauma Acute Care Surg.* **1978**, *18*, 533. [CrossRef]
31. Huelke, D.F.; Moffatt, E.A.; Mendelsohn, R.A.; Melvin, J.W. Cervical Fractures and Fracture Dislocations—An Overview. *SAE Trans.* **1979**, *88*, 462–468.
32. Huelke, D.F.; Nusholtz, G.S. Cervical spine biomechanics: A review of the literature. *J. Orthop. Res.* **1986**, *4*, 232–245. [CrossRef] [PubMed]
33. Myers, B.S.; Nightingale, R.W. Review: The Dynamics of Near Vertex Head Impact and its Role in Injury Prevention and the Complex Clinical Presentation of Basicranial and Cervical Spine Injury. *J. Crash Prev. Inj. Control* **1999**, *1*, 67–82. [CrossRef]
34. Myers, B.S.; Winkelstein, B.A. Epidemiology, Classification, Mechanism, and Tolerance of Human Cervical Spine Injuries. *Crit. Rev. Biomed. Eng.* **1995**, *23*, 307–409. [CrossRef]
35. Nusholtz, G.S.; Huelke, D.E.; Lux, P.; Alem, N.M.; Montalvo, F. *Cervical Spine Injury Mechanisms*; SAE International: Warrendale, PA, USA, 1983. [CrossRef]
36. Yoganandan, N.; Chirvi, S.; Pintar, F.A.; Banerjee, A.; Voo, L. *Injury Risk Curves for the Human Cervical Spine from Inferior-to-Superior Loading*; SAE International: Warrendale, PA, USA, 2018. [CrossRef]
37. Pintar, F.A.; Yoganandan, N.; Sances, A.; Reinartz, J.; Harris, G.; Larson, S.J. Kinematic and Anatomical Analysis of the Human Cervical Spinal Column Under Axial Loading. *SAE Trans.* **1989**, *98*, 1766–1789.
38. Burns, M.R.; Caldwell, A.J.; Shin, J.; Sochor, S.H.; Kopp, K.P.; Shaw, G.; Gepner, B.; Kerrigan, J.R. Assessing the Ability of Pressure Sensors Inserted into Intervertebral Discs to Detect Compression, Flexion, and Combined Flexion + Compression Loading. *SAE Int. J. Transp. Saf.* **2024**, *12*, 193–201. [CrossRef]
39. Nachemson, A.L. Disc Pressure Measurements. *Spine* **1981**, *6*, 93. [CrossRef]
40. Nachemson, A.; Morris, J.M. In Vivo measurements of intradiscal pressure. Discometry, a method for the determination of pressure in the lower lumbar discs. *J. Bone Jt. Surg. Am.* **1964**, *46*, 1077–1092. [CrossRef]
41. Dmitriev, A.E.; Cunningham, B.W.; Hu, N.; Sell, G.; Vigna, F.; McAfee, P.C. Adjacent level intradiscal pressure and segmental kinematics following a cervical total disc arthroplasty: An in vitro human cadaveric model. *Spine* **2005**, *30*, 1165–1172. [CrossRef]
42. Kretzer, R.M.; Hsu, W.; Hu, N.; Umekoji, H.; Jallo, G.I.; McAfee, P.C.; Tortolani, P.J.; Cunningham, B.W. Adjacent-level range of motion and intradiscal pressure after posterior cervical decompression and fixation: An in vitro human cadaveric model. *Spine* **2012**, *37*, E778–E785. [CrossRef]
43. Lou, J.; Li, Y.; Wang, B.; Meng, Y.; Gong, Q.; Liu, H. Biomechanical evaluation of cervical disc replacement with a novel prosthesis based on the physiological curvature of endplate. *J. Orthop. Surg.* **2018**, *13*, 41. [CrossRef] [PubMed]
44. Davies, M.A.; Bryant, S.C.; Larsen, S.P.; Murrey, D.B.; Nussman, D.S.; Laxer, E.B.; Darden, B.V. Comparison of cervical disk implants and cervical disk fusion treatments in human cadaveric models. *J. Biomech. Eng.* **2006**, *128*, 481–486. [CrossRef]
45. Lu, T.; Luo, C.; Ouyang, B.; Chen, Q.; Deng, Z. Effects of C5/C6 Intervertebral Space Distraction Height on Pressure on the Adjacent Intervertebral Disks and Articular Processes and Cervical Vertebrae Range of Motion. *Med. Sci. Monit. Int. Med. J. Exp. Clin. Res.* **2018**, *24*, 2533–2540. [CrossRef] [PubMed]
46. Lou, J.; Li, Y.; Wang, B.; Meng, Y.; Wu, T.; Liu, H. In vitro biomechanical comparison after fixed- and mobile-core artificial cervical disc replacement versus fusion. *Medicine* **2017**, *96*, e8291. [CrossRef]
47. Yan, Y.; Bell, K.M.; Hartman, R.A.; Hu, J.; Wang, W.; Kang, J.D.; Lee, J.Y. In vitro evaluation of translating and rotating plates using a robot testing system under follower load. *Eur. Spine J.* **2017**, *26*, 189–199. [CrossRef] [PubMed]
48. Bell, K.M.; Yan, Y.; Hartman, R.A.; Lee, J.Y. Influence of follower load application on moment-rotation parameters and intradiscal pressure in the cervical spine. *J. Biomech.* **2018**, *76*, 167–172. [CrossRef]
49. Whyte, T.; Barker, J.B.; Cronin, D.S.; Dumas, G.A.; Nolte, L.-P.; Cripton, P.A. Load-Sharing and Kinematics of the Human Cervical Spine Under Multi-Axial Transverse Shear Loading: Combined Experimental and Computational Investigation. *J. Biomech. Eng.* **2021**, *143*, 061013. [CrossRef]
50. Liu, Q.; Guo, Q.; Yang, J.; Zhang, P.; Xu, T.; Cheng, X.; Chen, J.; Guan, H.; Ni, B. Subaxial Cervical Intradiscal Pressure and Segmental Kinematics Following Atlantoaxial Fixation in Different Angles. *World Neurosurg.* **2016**, *87*, 521–528. [CrossRef]
51. King, A.I.; Viano, D.C.; Mizeres, N.; States, J.D. Humanitarian Benefits of Cadaver Research on Injury Prevention. *J. Trauma Acute Care Surg.* **1995**, *38*, 564. [CrossRef]
52. Adams, M.A.; McNally, D.S.; Dolan, P. "Stress" distributions inside intervertebral discs. The effects of age and degeneration. *J. Bone Jt. Surg. Br.* **1996**, *78*, 965–972. [CrossRef]
53. Lundon, K.; Bolton, K. Structure and Function of the Lumbar Intervertebral Disk in Health, Aging, and Pathologic Conditions. *J. Orthop. Sports Phys. Ther.* **2001**, *31*, 291–306. [CrossRef] [PubMed]
54. Matsumoto, M.; Fujimura, Y.; Suzuki, N.; Nishi, Y.; Nakamura, M.; Yabe, Y.; Shiga, H. MRI of cervical intervertebral discs in asymptomatic subjects. *J. Bone Jt. Surg. Br.* **1998**, *80-B*, 19–24. [CrossRef]

55. Miyazaki, M.; Hong, S.W.; Yoon, S.H.; Morishita, Y.; Wang, J.C. Reliability of a Magnetic Resonance Imaging-based Grading System for Cervical Intervertebral Disc Degeneration. *Clin. Spine Surg.* **2008**, *21*, 288. [CrossRef]
56. Jacobs, L.J.; Chen, A.F.; Kang, J.D.; Lee, J.Y. Reliable Magnetic Resonance Imaging Based Grading System for Cervical Intervertebral Disc Degeneration. *Asian Spine J.* **2016**, *10*, 70–74. [CrossRef]
57. Otaki, H.; Otani, K.; Watanabe, T.; Sekiguchi, M.; Konno, S. Associations between clinical neck symptoms and various evaluations of cervical intervertebral disc degeneration by magnetic resonance imaging. *Fukushima J. Med. Sci.* **2021**, *67*, 107–118. [CrossRef]
58. Skrzypiec, D.M.; Pollintine, P.; Przybyla, A.; Dolan, P.; Adams, M.A. The internal mechanical properties of cervical intervertebral discs as revealed by stress profilometry. *Eur. Spine J.* **2007**, *16*, 1701–1709. [CrossRef] [PubMed]
59. Kerrigan, J.R.; Foster, J.B.; Sochor, M.; Forman, J.; Toczyski, J.; Roberts, C.W.; Crandall, J.R. Axial Compression Injury Tolerance of the Cervical Spine: Initial Results. *Traffic Inj. Prev.* **2014**, *15*, S238–S269. [CrossRef]
60. Patwardhan, A.G.; Khayatzadeh, S.; Havey, R.M.; Voronov, L.I.; Smith, Z.A.; Kalmanson, O.; Ghanayem, A.J.; Sears, W. Cervical sagittal balance: A biomechanical perspective can help clinical practice. *Eur. Spine J.* **2018**, *27*, 25–38. [CrossRef]
61. Foust, D.R.; Chaffin, D.B.; Snyder, R.G.; Baum, J.K. Cervical Range of Motion and Dynamic Response and Strength of Cervical Muscles. *SAE Trans.* **1973**, *82*, 3222–3234.
62. Pan, F.; Arshad, R.; Zander, T.; Reitmaier, S.; Schroll, A.; Schmidt, H. The effect of age and sex on the cervical range of motion—A systematic review and meta-analysis. *J. Biomech.* **2018**, *75*, 13–27. [CrossRef]
63. Nachemson, A. Lumbar Intradiscal Pressure: Experimental Studies on Post-Mortem Material. *Acta Orthop. Scand.* **1960**, *31*, 1–104. [CrossRef] [PubMed]
64. Magee, D.J.; Manske, R.C. *Orthopedic Physical Assessment*, 7th ed.; Elsevier Educate: St. Louis, MO, USA, 2020. Available online: https://www.educate.elsevier.com/book/details/9780323749510 (accessed on 18 May 2025).
65. Gilad, I.; Nissan, M. A Study of Vertebra and Disc Geometric Relations of the Human Cervical and Lumbar Spine. *Spine* **1986**, *11*, 154–157. [CrossRef] [PubMed]
66. Soltan, N.; Svensson, M.Y.; Jones, C.F.; Cripton, P.A.; Siegmund, G.P. In Vivo Pressure Responses of the Cervical Cerebrospinal Fluid in a Porcine Model of Extension and Flexion Whiplash Exposures. *Ann. Biomed. Eng.* **2025**, *53*, 1165–1179. [CrossRef] [PubMed]
67. Liu, M.; Quarrington, R.D.; Sandoz, B.; Robertson, W.S.P.; Jones, C.F. Evaluation of Apparatus and Protocols to Measure Human Passive Neck Stiffness and Range of Motion. *Ann. Biomed. Eng.* **2024**, *52*, 2178–2192. [CrossRef]