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Basic Science

Facet joint contact pressure is not significantly affected by ProDisc cervical disc arthroplasty in sagittal bending: a single-level cadaveric study

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Abstract

BACKGROUND CONTEXT: Total disc arthroplasty is a motion-preserving spinal procedure that has been investigated for its impact on spinal motions and adjacent-level degeneration. However, the effects of disc arthroplasty on facet joint biomechanics remain undefined despite the critical role of these posterior elements on guiding and limiting spinal motion.

PURPOSE: The goal was to measure the pressure in the facet joint in cadaveric human cervical spines subjected to sagittal bending before and after implantation of the ProDisc-C (Synthes Spine Company, L.P, West Chester, PA, USA).

STUDY DESIGN: A biomechanical study was performed using cadaveric human cervical spines during sagittal bending in the intact and implanted conditions.

METHODS: Seven C2–T1 osteoligamentous cadaveric cervical spines were instrumented with a transducer to measure the C5–C6 facet pressure profiles during physiological sagittal bending, before and after implantation of a ProDisc-C at that level. Rotations of the index segment and global cervical spine were also quantified.

RESULTS: The mean C5–C6 range of motion significantly increased ($p=.009$) from $9.6°\pm5.1°$ in the intact condition to $16.2°\pm3.6°$ after implantation. However, despite such changes in rotation, there was no significant difference in the facet contact pressure during extension between the intact (64 ± 30 kPa) and implanted (44 ± 55 kPa) conditions. Similarly, there was no difference in facet pressure developed during flexion.

CONCLUSIONS: Although implantation of a ProDisc-C arthroplasty device at the C5–C6 level increases angular rotations, it does not significantly alter the local facet pressure at the index level in flexion or extension. Using a technique that preserves the capsular ligament, this study provides the first direct measurement of cervical facet pressure in a disc arthroplasty condition.

Keywords: Disc arthroplasty; Cervical spine; Biomechanics; Facet joint; Contact pressure

FDA device/drug status: Approved (ProDisc-C).

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Introduction

Total disc arthroplasty (TDA) has received increasing interest as a surgical treatment option for degenerative disease of the cervical spine. Despite differences in implant designs, many clinical studies have demonstrated that patient outcomes are at least equivalent to traditional anterior cervical fusion [1–5], further validating the role for TDA in spine care. As such, an understanding of the effect of disc replacement devices on spinal mechanics is critical for the assessment and future development and enhancement of disc replacement technology. To date, the principal focus has been in defining the biomechanics at the adjacent segment because preventing adjacent segment disease is a potential major advantage of TDA. Although many studies have defined the effects of arthroplasty on the mechanics at adjacent levels [6–11], few have investigated the effects of total disc replacement on the posterior elements of the index motion segment, namely, the facet joints [12,13]. The facet joints have been shown to be critical in determining the type and extent of motion of the lumbar spine in concert with the arthroplasty device [14,15]. However, analogous studies in the cervical spine have not been performed. Because the effect of disc replacement on index-level facet joint contact in the cervical spine has not been quantified, facet disease is currently considered a contraindication to implantation of a disc replacement device. Long-term degeneration of the facet joints has been reported in up to 19% of patients in a cervical disc arthroplasty clinical series [9]; yet, little is known about the pathomechanisms of these changes or even how a disc implant affects cervical facet biomechanics. It is important to define the local mechanical environment of the facet joint in the context of disc arthroplasty. Such mechanical insight helps to evaluate potential pathomechanisms; yet, these data are currently unavailable.

One way of defining facet joint biomechanics is through the measurement of the contact pressure in the articulation [16–20]. However, in both native and post-arthroplasty conditions, studies have been limited primarily to finite element analysis. The most obvious challenge in measuring facet contact pressure in the cervical spine is the small size and varied orientation of the joint space. Also, most pressure measurement techniques require disruption of the joint via capsular ligament transection, which itself is sufficient to alter the mechanics of a motion segment [21,22]. In the lumbar facet joint, which has a larger contact region and undergoes less coupled motion, contact pressures have been measured in cadavers by inserting pressure-sensitive films in the joint space together with the implantation of both disc arthroplasty and dynamic stabilization devices [14,23]. Despite the fact that films violate the facet's capsule, they may be suitable for use in the lumbar spine, which sustains greater axial loading and does not rely on the capsular ligaments for stability. In contrast, the cervical capsular ligaments have been shown to contribute to the overall stability of the cervical spine [24]. Consequently, any measurement sensor that requires disrupting the capsular ligament may destabilize the joint. Given the inherent mechanical disruption caused by disc implantation, including transection of the anterior and posterior longitudinal ligaments, and partial removal of the uncovertebral joints, capsular preservation is an important prerequisite to accurately measure the facet joint articular contact in the post-implant cervical spine.

To date, only one cadaveric study has examined contact forces in the facet joints after cervical disc arthroplasty using both a semi-constrained device (ProDisc-C; Synthes Spine Company, L.P, West Chester, PA, USA) and an unconstrained device (Prestige; Medtronic, Minneapolis, MN, USA) [12]. In a similar study, Chang et al. compared the rotational motions of spines with implants or cervical fusion with those of intact spines [25]. Those authors found extension to be the only motion to significantly alter facet joint contact force for either implant. However, the forces were estimated by interpolating strains in the laminae; this approach can be subject to errors because the mechanical environment of the bony laminae serves only as a proxy for the intra-articular forces, and in sagittal bending, in particular, the surrounding musculature and soft tissues have different effects on both the laminae and the articulation of the facets [25]. Arguably, understanding the effects of disc arthroplasty for cervical spine sagittal bending is important because flexion/extension is most clinically relevant and measurable with routine dynamic radiographs. In addition, finite element analyses suggest that factors such as implant height and center of rotation affect sagittal kinematics and facet force [20,26], indicating the need to properly evaluate the facet contact for the normal intact case. The objective of this study was to measure cervical facet contact pressures using a minimally invasive capsule sparing method in cervical spine sagittal bending before and after implantation of a disc arthroplasty device. The semi-constrained ProDisc-C was selected because of the large increase in facet contact force estimated in extension that was previously reported [12].

Materials and methods

Fresh-frozen male human C2–T1 cadaveric cervical spines (n=7; 59±12 years) were obtained from MedCure (Portland, OR, USA). Younger specimens were preferentially selected to best match the clinical age range for disc arthroplasty implantation. Because of the potential effects of degeneration on loading and kinematics [17], specimens were screened to minimize bridging osteophytic disease and facet degeneration with three-dimensional (3D) fluoroscopy (Arcadis Orbic 3D; Siemens AG, Munich, Germany). Disc and segmental degenerations were graded radiographically [27,28]. Specimens were dissected, and C2–T1 was cast in aluminum cups with Flow Stone potting material (Whip Mix Corp., Louisville, KY, USA). The paraspinal muscles were removed while exposing, but not violating, the bilateral facet joint capsules. Reflective markers were attached to the C5 and C6 vertebrae, as well as the C2 and T1 casting cups, to facilitate both segmental and global motion tracking of each specimen (Fig. 1).

A tip-mounted pressure probe (XCEL-100-50A; Kulite Semiconductor Products, Leonia, NJ, USA) was used to measure contact pressure in the left C5–C6 facet joint, using an approach that does not require transection of the joint capsule [29]. Briefly, a hole was drilled under fluoroscopic guidance in the posterior aspect of the C5 lateral mass with an orientation perpendicular to the C6 articular surface in the sagittal plane (Fig. 2, Left). Care was taken to avoid positioning the sensor in the extreme posterior portion of the C5 lateral mass that does not articulate with the C6 surface. The pressure probe was press-fit into the bone, and its location was confirmed with 3D imaging (Fig. 2, Left). From previous work, the optimal angle of the probe relative to the C6 articular surface was within 5° off of the surface normal [22]; the probe angle was verified for each specimen using OsiriX image processing software (Pixmeo Sarl, Geneva, Switzerland).

A customized testing frame was used to impose controlled flexion and extension. Simultaneously global (C2–T1) and segmental (C5–C6) vertebral motions were measured, along with the contact pressure in the left C5–C6 facet joint during testing (Fig. 1). Each specimen was rigidly fixed to the test frame through its T1 casting cup that was coupled to a six-axis load cell (model 4386; RA Denton, Inc., Rochester Hills, MI, USA). Flexion and extension were applied by a pneumatic piston-driven cable system controlled using a customized LabVIEW program (National Instruments, Austin, TX, USA) to pull at the end of the moment arm attached to the superior C2 cup (Fig. 1). A 5-N force was applied over a 1-second loading phase to generate a physiological sagittal bending moment of 2.0 to 2.5 Nm [12,19,30]. Each specimen was also loaded by a compressive preload of 14 N from the combined weights of the superior cup, casting material, and moment arm. This preload was modest but prevented the need for counterweights to maintain the specimen in an upright configuration that would be required with greater loads [29]. Motion tracking of the markers on the specimen was performed with an integrated four-camera optical-analog system (PEAK Motus 8.0; Vicon, Denver, CO, USA) that was synchronized to acquire image data along with the data from both the load cell and pressure probe at 600 Hz.

Intact specimens were first preconditioned in sagittal bending, followed by application of flexion and extension loading. Because maximal facet contact occurs when the spine is furthest from its neutral posture [31,32], sagittal bending was applied with the specimen initially resting in a flexed or extended position away from its neutral erect position, simulating the transition from the neutral zone (NZ) to the elastic zone [29]. The range of motion between the naturally flexed and extended positions of the specimens was taken as the neutral zone range of motion (NZROM). Using the markers on the cups and in the vertebrae, both global (C2–T1) and segmental (C5–C6) NZROMs were defined for each specimen. The total global and segmental ranges of motion for each specimen were

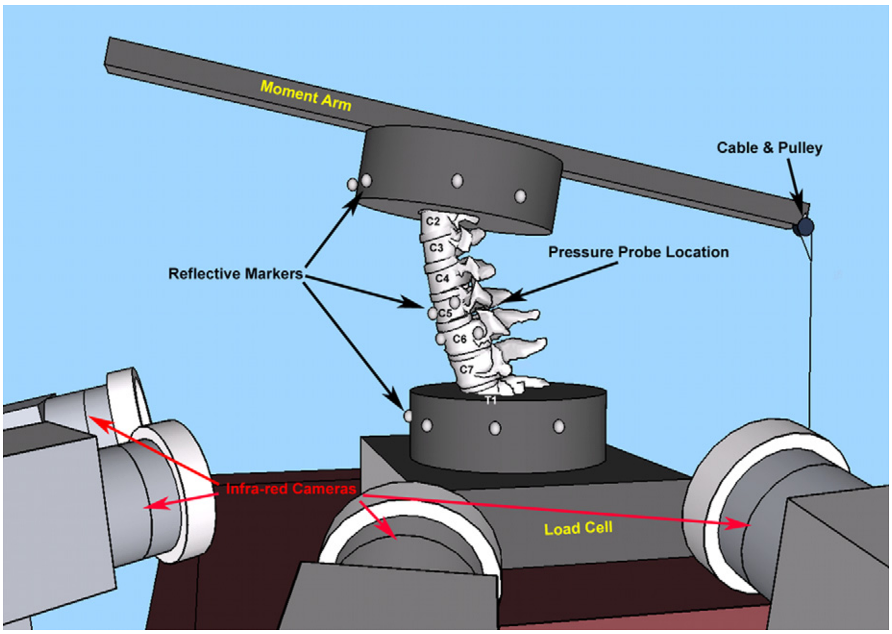

Fig. 1. Schematic of the test setup showing a cadaveric cervical specimen with C2 and T1 cast in cups that are coupled to the moment arm and load cell. Reflective markers are affixed to the C5 and C6 vertebrae and the C2 and T1 cups for motion tracking by the infrared cameras. In this illustration, the moment arm is connected to the cable and pulley system for the application of extension.

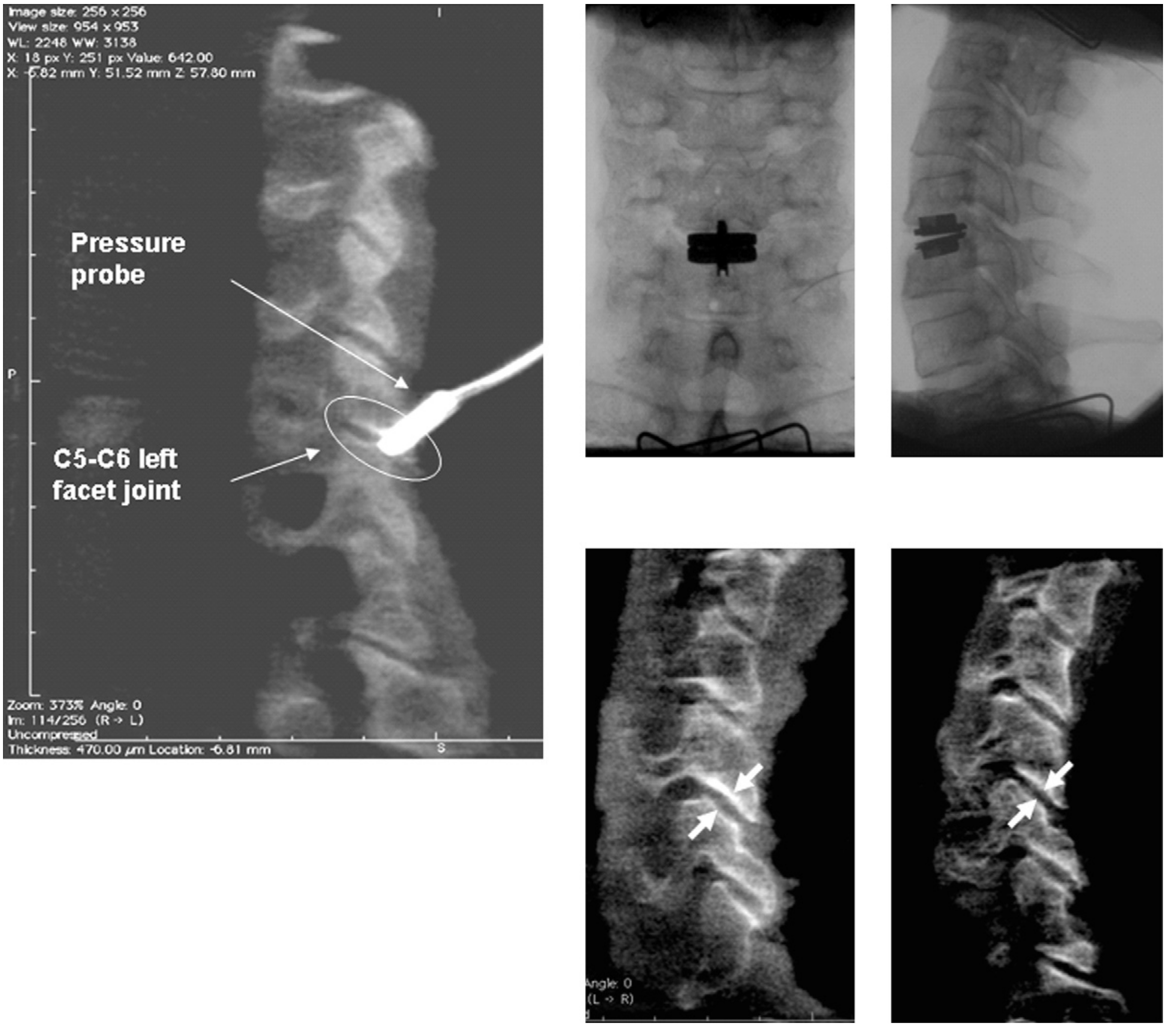

Fig. 2. (Left) Representative fluoroscopic image of a specimen (Specimen #J2) showing the pressure probe inserted in the C5–C6 left facet joint. (Top Right) Representative frontal and lateral radiographs showing a ProDisc-C implant at the C5–C6 level for Specimen #J7. (Bottom Right) Sagittal radiographs of the left posterior column of Specimen #J7 showing that the left C5–C6 facet gap (arrows) is unchanged before and after ProDisc-C implantation.

also calculated by summing NZROM and rotations during the flexion and extension.

After testing in the intact condition, a ProDisc-C (Synthes Spine Company, LP) was implanted at C5–C6. The choice of implant size (ie, height, depth, and width) was best fit to each individual specimen based on trial spacer sizing with parallel end plate distraction according to the standard operative technique. A minimal (1–2 mm) bilateral uncinatectomy and complete posterior longitudinal ligament removal were performed in all cases. All specimens were reimaged with 3D fluoroscopy after implantation. Proper anteroposterior implant position was determined using lateral fluoroscopy images and the OsiriX software (Fig. 2, Top Right). In addition, the height of the disc space and ipsilateral and contralateral facet space distances at C5–C6 were measured in the sagittal plane pre- and post-implantation to ensure that no overdistraction occurred as a result of disc implantation (Fig. 2, Bottom Right). The disc height and left and right facet joint spaces for each specimen pre- and post-disc arthroplasty implantation were compared by separate paired *t* tests (Systat 10; Systat Software, Chicago, IL, USA). The flexion and extension loading protocols were repeated again after ProDisc-C implantation.

For each specimen in each direction of loading (extension and flexion), the global and segmental motions were determined at the common moment achieved in both the intact and implanted conditions. In addition, the change in facet pressure and rate of loading over the common applied moment were also determined. Lastly, the greatest change in pressure achieved during the loading phase (Peak P) was also recorded for each condition. For both the intact and implanted conditions, the change in sagittal moment (ΔM), global angle ($\Delta\theta_{C2-T1}$), segmental angle ($\Delta\theta_{C5-C6}$), change in facet pressure (ΔP), maximum or minimum pressure (Peak P), and the loading rate (ΔM/t) were compared by paired *t* tests between flexion and extension. For each of the flexion and extension directions, these values were also compared between the intact and implanted conditions using paired t test. Similarly, the global (C2–T1 NZROM) and segmental (C5–C6 NZROM) NZROMs were also compared between the intact and implanted conditions for each direction of loading.

Results

All specimens had little to no osteophytic disease, with the exception of one specimen (#J8), which was rated as moderate (Table 1). There was no difference in the average disc space height ($p=.408$) or in the facet joint space on either the left ($p=.233$) or the right ($p=.834$) side, between the pre- and post-implantation conditions (Table 1). The mean applied moment was 2.1 ± 0.2 Nm in extension and 2.4 ± 0.4 Nm in flexion, with all specimens undergoing at least 1.9 Nm of moment in each of extension and flexion (Table 2). However, during testing of one specimen (#J3), the loading system generated only 0.8 Nm of flexion moment, so only extension data were available. The average total global range of motion was $55.5°\pm18.0°$ in the intact condition and significantly increased ($p<.001$) after the ProDisc-C implantation ($63.0°\pm19.0°$) (Fig. 3, Top). At C5–C6, the total segmental range of motion also increased significantly ($p=.009$) from $9.6°\pm5.1°$ in the intact condition to $16.2°\pm3.6°$ in the implanted condition (Fig. 3, Bottom). Global rotation in flexion significantly increased ($p=.018$) from the intact ($8.3°\pm1.6°$) to implanted ($10.4°\pm0.5°$) condition, but this increase was not significant at the level of the C5–C6 segment (Fig. 3; Table 2). However, there was no significant difference in global or segmental rotation between the intact and implanted conditions during extension (Fig. 3; Table 2). The NZ contributions to total range of motion were significantly increased (global: $p=.019$; segmental: $p=.009$) after implantation compared with the intact condition (Fig. 3; Table 2).

In extension, facet contact pressure increased with applied load. However, negative pressures developed in flexion. There was a significant difference ($p\leq.01$) in the change in contact pressure for the intact case between extension and flexion; this difference was not significant in the implanted condition despite pressures being greater during extension than flexion (Table 2). Despite significant changes in rotation (Fig. 3; Table 2), there was no significant difference in the facet contact pressure during extension between the intact (64 ± 30 kPa) and implanted (44 ± 55 kPa) conditions (Fig. 4; Table 2). Furthermore, the peak pressure established during extension was also not changed by the implantation of the ProDisc-C (Table 2). In flexion, positive facet contact pressure was developed only in the implanted condition and not in the intact case (Table 2). Although there was a significant difference between the peak pressures in flexion, the positive pressure that developed in the implanted condition was still relatively small in most specimens (Table 2).

In general, the contact pressures that developed in the implanted condition were more variable than those in the intact condition (Figs. 4 and 5; Table 2). In particular, the moment-pressure responses were more linear in the intact condition, whereas pressure increased more quickly in the implanted condition and reached its peak before the maximum moment was generated in most cases (Fig. 5). As a consequence, the moment-pressure relationship was generally less linear in the implanted condition. The rate of loading was similar in flexion and extension in each of the intact and implanted conditions (Table 2). However, the rate of loading was steeper (ie, faster) in the implanted condition than in the intact condition. This increase was significant ($p=.016$) in extension but not in flexion (Table 2).

Discussion

Changes in facet joint biomechanics have been the least well-understood aspect of disc replacement technology, owing to the limited accessibility of the joint and a lack of adequate technology to make relevant and meaningful measurements. This is the first study to our knowledge to measure contact pressure in the cervical facet joint of the human cadaver in the context of disc implantation. The present study determined that despite an increase in both the segmental and global rotations in the NZ and in the overall sagittal range of motion of the specimens after the implantation of the ProDisc-C at C5–C6, the facet contact

Table 1
Summary of the specimen data and ProDisc-C implant sizes used

				Disc height (mm)		Facet space (mm)				Implanted ProDisc-C			
						Left		Right					
Specimen	Age (y)	Sex	Disc degeneration	Intact	Implanted	Intact	Implanted	Intact	Implanted	Footprint	Depth (mm)	Width (mm)	Height (mm)
J2	37	Male	None	6.1	7.1	1.6	1.8	2.2	3.4	LD	16	17	5
J3	59	Male	None	8.2	6.1	1.9	2.1	2.4	2.7	L	14	17	5
J4	51	Male	None	6.0	7.1	1.8	2.3	2.5	1.5	LD	16	17	5
J5	65	Male	None	5.7	5.4	2.3	2.3	2.8	2.5	L	14	17	6
J7	54	Male	None	6.0	6.5	3.1	2.8	3.4	3.5	L	14	17	5
J8	78	Male	Moderate	3.7	5.3	2.0	2.3	2.8	3.2	M	12	15	5
J11	69	Male	Minimal	5.2	6.3	2.1	2.1	3.4	3.1	MD	14	15	5

LD, large deep; L, large; M, medium; MD, medium deep.

Table 2
Summary of kinetics, kinematics, and pressure measurements during sagittal bending of cadaveric cervical spines before and after ProDisc-C implantation at the C5–C6 level

			ΔM (Nm)		$\Delta\theta_{C2-T1}$ (°)		$\Delta\theta_{C5-C6}$ (°)		ΔP (kPa)		Peak P (kPa)		ΔM/t (Nm/s)	
Specimen	C2–T1 NZROM (°)	C5–C6 NZROM (°)	Ext	Flex	Ext	Flex	Ext	Flex	Ext	Flex	Ext	Flex	Ext	Flex
Intact														
J2	73.4	15.7	2.2	2.4	10.5	5.6	2.0	1.0	101	−13	92	−62.4	1.8	2.7
J3	N/A	N/A	2.0	N/A	8.8	N/A	3.8	N/A	47	N/A	108	N/A	2.1	N/A
J4	34.1	6.8	1.9	2.3	6.7	8.0	1.1	1.6	24	1	37	−3.2	3.7	2.1
J5	33.3	5.6	1.9	2.1	8.6	8.7	1.4	1.5	89	−12	73	−10.5	1.6	1.9
J7	38.2	4.7	2.3	1.9	7.6	9.5	0.2	0.6	77	−25	70	−47.9	3.1	2.2
J8	20.5	2.9	2.1	2.9	7.4	7.7	0.9	0.5	28	−6	26	−9.8	2.1	2.5
J11	33.1	7.2	2.2	2.7	9.9	10.2	2.6	1.1	80	−2	88	−4.7	1.7	5.6
Mean (SD)	38.7 (18.0)	7.1 (4.5)	2.1 (0.2)	2.4 (0.4)	8.5 (1.4)	8.3 (1.6)	1.7 (1.2)	1.1 (0.5)	64 (30)	−10 (9)	71 (30)	−23 (25)	2.3 (0.8)	2.8 (1.4)
p-Values: Ext vs. Flex			.178		.381		.195		.005*		.010*		.564	
Implanted														
J2	79.0	16.0	2.2	2.4	10.6	10.1	3.3	2.4	134	−2	165	3	3.5	3.2
J3	N/A	N/A	2.0	N/A	6.5	N/A	2.5	N/A	19	N/A	25	N/A	1.9	N/A
J4	35.0	10.6	1.9	2.3	8.3	10.9	1.3	0.7	33	−3	45	0	4.3	2.2
J5	41.9	11.4	1.9	2.1	7.7	11.0	2.4	2.3	19	48	42	41	2.5	2.7
J7	41.9	13.5	2.3	1.9	9.2	10.0	2.9	2.3	−7	−4	45	−5	4.4	4.0
J8	24.5	7.8	2.1	2.9	10.0	9.8	2.2	2.1	3	75	14	24	3.7	4.9
J11	34.2	11.3	2.2	2.7	13.1	10.7	3.0	1.7	109	−11	255	−10	4.7	5.2
Mean (SD)	42.8 (18.9)	11.7 (2.8)	2.1 (0.2)	2.4 (0.4)	9.3 (2.2)	10.4 (0.5)	2.5 (0.7)	1.9 (0.7)	44 (55)	17 (36)	85 (90)	9 (19)	3.6 (1.0)	3.7 (1.2)
p-Values: Ext vs. Flex			.178		.771		.032*		.477		.109		.766	
p-Values intact vs. ProDisc-C	.019*	.009*	N/A	N/A	.321	.018*	.146	.087	.313	.128	.671	.036*	.016*	.088

NZROM, neutral zone range of motion; Ext, extension; Flex, flexion; N/A, not applicable; SD, standard deviation.
* Significant difference.

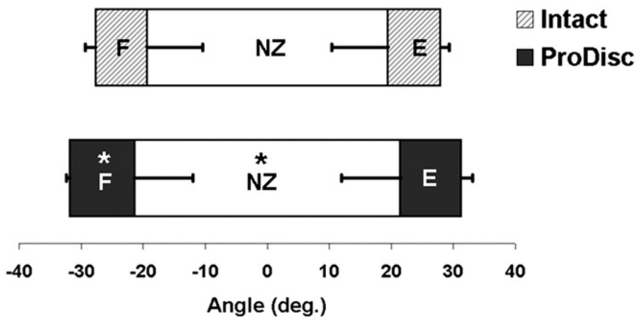

Fig. 3. Box-and-whiskers plots of the (Top) global (C2–T1) and (Bottom) segmental (C5–C6) range of motion before and after ProDisc-C implantation. The white central band represents the average neutral zone range of motion of all the specimens. The shaded boxes correspond to the rotations during flexion (F) and extension (E). *Significant differences between the intact and ProDisc configurations. NZ, neutral zone.

pressures were not increased (Figs. 3 and 4; Table 2). Furthermore, although the global and segmental rotations increased after ProDisc-C implantation in flexion, only the peak facet pressure was significantly increased in the implanted condition compared with intact (Table 2).

An increased range of motion after the implantation of cervical and lumbar Pro-Disc implants and other arthroplasty devices has been previously reported in a number of clinical, cadaveric, and computational studies [26,33–35].

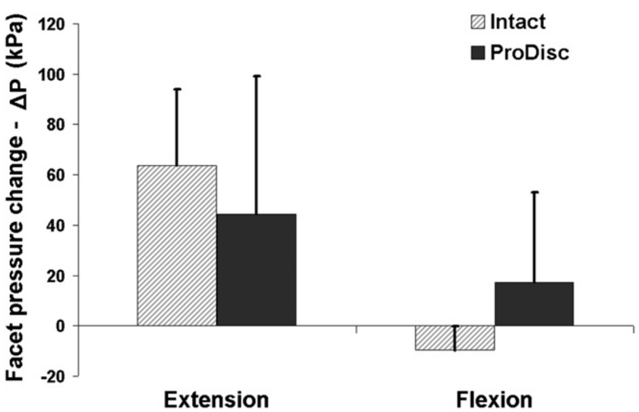

Fig. 4. Facet pressure change (ΔP) measured in the left C5–C6 facet joint during extension and flexion for specimens before (Intact) and after (ProDisc) implantation.

Clinical studies have also documented increases in cervical range of motion after ProDisc-C implantation [34,36,37]. Although the increase in segmental range of motion measured in our study is larger than that reported in clinical reports from 3 weeks after implantation [34], it is similar to clinical range of motion measured 6 to 14 months after implantation [34,36,37]. The differences observed between our study and the early time points after surgery may be because of the fact that the musculature that is active in patients, but absent in a cadaveric study, may limit the range of motion. Furthermore, the increase in range of motion after disc implantation observed in the present study is most likely not due to overdistraction because there was no change in the disc space in the implanted condition compared with the intact condition (Table 1). It is possible that modification of the segmental motions that may be caused by disc arthroplasty could eventually lead to facet degeneration through supraphysiological loading of the facet and its tissues [9,38]. However, cadaveric studies, like the one reported here, can provide only a short-term snapshot of the relationship between spinal motions, facet joint loading, and biomechanics and should not be taken as directly comparable with the clinical scenario in which physiological factors can modulate outcomes.

Unlike kinematic information, there are very limited data describing the facet joint biomechanics after disc arthroplasty and if or how they are modified in the cervical spine. Although a previous cadaveric study did report the facet force to increase after the implantation of a ProDisc-C during extension, the study by Chang et al. [12] used uniaxial surface strain gages mounted on the articular pillar to indirectly estimate the force transmitted through the facets. Accordingly, such measurements were subjected to bias inherent in the properties and/or the removal of the facet tissues required to implement the gauges [39]. Moreover, neither finite element analysis of cervical disc arthroplasty [11,18] nor in vitro studies of lumbar disc arthroplasty support a significant increase in facet force after arthroplasty [35,40]. In our study, facet pressure changes (ΔP) and peaks were measured directly without modifying the mechanical integrity of the facet joint or the motion segment. Owing to the anatomy of the cervical spine and its mechanical loading, the facet pressures measured in this region would be expected to be smaller than those measured previously in the lumbar region [31,41]. However, other parameters such as the anatomic orientation of the facet joints and the positioning and dimensions of the artificial disc also influence facet joint kinematics and articular loading.

In the present study, the shortest available implant heights (5 mm) were used in all but one of the specimens (Table 1). Although the facet pressure after implantation trended toward being lower in extension and greater in flexion than in the intact condition (Fig. 5; Table 2), these differences were not significant. Chang et al. [12] reported a significant increase in facet pressure in extension using

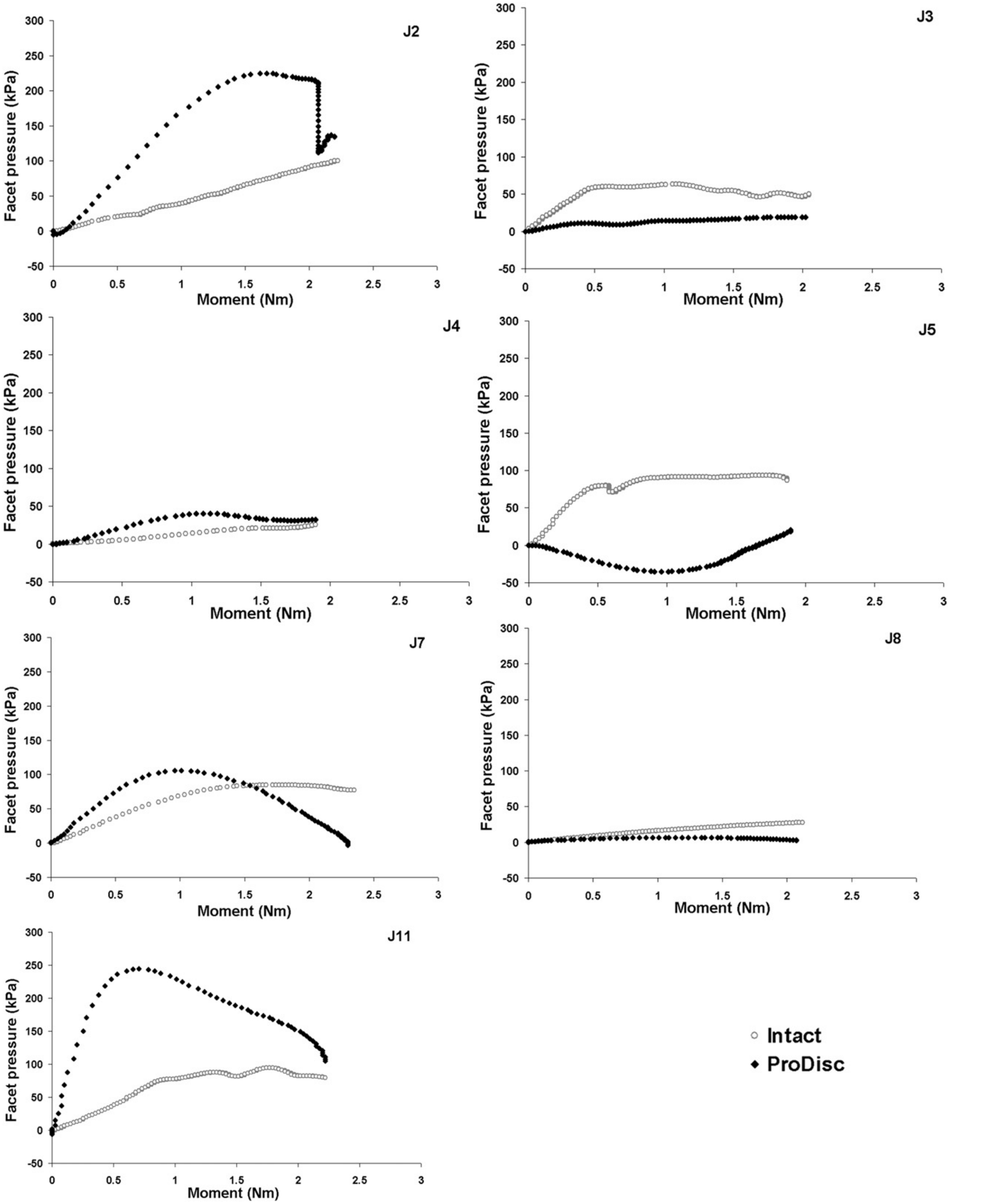

Fig. 5. Pressure-moment responses for each specimen subjected to extension before (Intact) and after (ProDisc) implantation. Pressure rises quicker and higher with increasing moment in the implanted (ProDisc) specimens, peaking before the maximum moment is generated. The moment-pressure relationship is generally less linear in the ProDisc condition.

ProDisc-C implants that were 7 mm in height, which are the tallest available. The discrepancy in outcomes between our study and Chang's could be because of the difference in the height of the artificial discs and/or the differences in measurement techniques used (pressure probe and strain gages, respectively). Taller implants can increase the joint space and decrease the amount of articular contact [42], which can modify both the location and extent of articular contact and also likely reduce the facet force. This notion is supported by a finite element study in which facet contact force was found to be greater in the intact condition for flexion with the shortest implant, whereas it is increased over the intact condition for all implants, regardless of height, in extension [11]. In our study, the disc and facet joint spaces were measured before and after implantation of the ProDisc-C (Fig. 2), and no changes were detected (Table 1). As such, the facet pressure measurements in this study reflect only those changes that are due to the loading in the joint and do not represent any change that may be because of altered joint space geometry resulting from the implant. Therefore, the differences in the changes in facet pressure between the present study and that by Chang et al. [12] could be because of the different sizes of the ProDisc-C implants used in the two studies. However, other parameters, such as the anteroposterior placement of the implant, have also been shown to influence facet pressure [26,43]. Moreover, this study did not investigate the adjacent-level mechanics after the implant placement. Accordingly, it is not known if the overall joint kinematics, kinetics, and pressure profiles are modified in those neighboring joints. Additional studies investigating these and other responses will be important for understanding a more complete picture of the spine's response.

In addition to the altered kinematics after ProDisc-C implantation (Fig. 3), the fact that the moment ($\Delta M/t$) was achieved quicker after implantation (Table 2) suggests that the facets come in contact faster and earlier with the ProDisc-C. This is especially evident in extension (Fig. 5; Table 2). The geometric center of rotation of the lumbar spine with a disc implant has been shown to not always be aligned with the instantaneous axis of rotation of the spinal segment [14]. In addition, computational modeling of cervical total disc replacement predicted that fixed center of rotation implants do not uniformly overload the facet joints, which is not the case with other mobile implant types [18]. The ProDisc-C has a fixed center of rotation that may constrain segmental motion and might force the facet joints into earlier and/or non-physiological contact during extension. However, the changes in facet pressure (ΔP) and the peak pressure (Peak P) measured for the implanted specimens were not different from the intact condition in extension (Table 2). Because the pressure measured in both conditions was small and similar (Fig. 4; Table 2), the changes in the local joint contact mechanics that are produced because of the implantation of this artificial disc are not necessarily non-physiological. However, the changes in their location and persistence may be injurious to the cartilaginous tissue and could lead to tissue degradation and joint degeneration in the long term.

Overall, pressure changes were more variable in both flexion and extension after the disc implantation in comparison with the intact condition (Figs. 4 and 5). This variability was particularly evident in the peak pressures reached during flexion, which were both negative and positive (Table 2). Although all the specimens unloaded the facet during flexion in the intact condition (Fig. 4; Table 2), three specimens did develop a *compressive* pressure in the facet during flexion in the implanted condition (Table 2). This may imply that the local tissue mechanics are altered nonuniformly after the implantation and could be affected by other parameters such as local cartilaginous anatomy, orientation of the facet joints, and/or adjacent segment responses [13]. Despite large variations, the peak pressures during bending did remain one or two orders of magnitude smaller than those reported in the cadaveric lumbar spine under combined compression (up to 700 N) and sagittal bending (up to 15 Nm) [31,41]. The loading magnitudes used in the present study of the cervical spine were less than in those studies of the lumbar spine because the cervical spine is not exposed to such high loads. The large differences in facet pressures reported for the cervical and lumbar studies could indeed be because of the differences in the imposed loading conditions. Certainly, facet pressure depends on both the axial load and bending moment applied to the intervertebral joint. Although the present study implemented a small axial compressive preload, the sagittal bending applied was physiological and so the resulting pressure changes represent physiologically meaningful estimates of cartilage loading. Over time, the small increases in pressure and rotation measured in the implanted specimens of our study (Figs. 3 and 4; Table 2) might have a detrimental effect on the cartilaginous structure and the facet joint mechanics. However, this hypothesis cannot be studied in a cadaveric model but merits further investigation in vivo. For instance, facet arthrosis has been reported as a long-term pathology in some lumbar disc arthroplasty patients [44,45].

Although the average age of the cadaveric specimens used in this study was generally older than the average age of patients reported in clinical studies of cervical disc arthroplasty [1–3], the majority (ie, five) of the specimens in the present study did not exhibit any disc degeneration; the other two had minimal or moderate disc degeneration, respectively (Table 1). Also, there were no bony defects or osteophytes of the articular pillar. Therefore, the effects of age and confounding factors of degeneration on the spinal motions that are usually encountered in cadaveric studies were minimized in our study. The pressure measurements were acquired using a technique to make very focal measurements, which may not fully capture the greatest facet contact pressure developed during all modes of loading. However, care was taken to position the probe in the area where articular contact occurs during sagittal bending [16,22,46]. Indeed, the probe placement was near the posterior aspect of the lateral mass and was optimized for measuring pressure during extension when facet contact is maximal as suggested by their anatomic orientation.

Conclusions

This study provides the first direct measurement of cervical facet pressure in a disc arthroplasty condition. Local cervical facet joint contact pressures were not significantly changed after the implantation of a ProDisc-C device at the C5–C6 level in osteoligamentous human cadaveric specimens during physiological sagittal bending. The changes in and peak pressures determined in this study suggest that this fixed center of rotation implant does not overload the facet joints. To more accurately define the loading environment of the facets, additional studies are needed to define the local and global spatiotemporal responses of the facet joints for more complicated neck motions and loading scenarios in the context of disc arthroplasty.

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