Spine

SPINE Volume 36, Number 15, pp 1197–1203
©2011, Lippincott Williams & Wilkins

CERVICAL SPINE

Pressure Measurement in the Cervical Spinal Facet Joint

Considerations for Maintaining Joint Anatomy and an Intact Capsule

Nicolas V. Jaumard, PhD,* Joel A. Bauman, MD,* William C. Welch, MD,* and Beth A. Winkelstein, PhD,*†

Study Design. A novel noninvasive approach to measure facet joint pressure in the cervical spine was investigated using a tip-mounted transducer that can be inserted through a hole in the bony lateral mass. This technique is advantageous because it does not require resection of the joint capsule, but there are potential issues regarding its applicability that are addressed.

Objective. The objective was to evaluate the effect of a tip-mounted pressure probe's position and orientation on contact pressure measurements in biomechanical experiments.

Summary of Background Data. Measurements of direct contact pressure in the facet joint of cadaveric spines have been obtained *via* pressure-sensitive films. However, that method requires the resection of the facet capsule, which can alter the overall joint's mechanical behavior and can affect the measured contact pressures.

Methods. Influence of position and orientation on probe measurements was evaluated in companion surrogate and cadaveric investigations. The probe was placed in the facet of an anatomic vertebral C4/5 surrogate undergoing sagittal bending moments. Pressure-sensitive paper was used to map contact regions in the joint of the surrogate and cadaveric cervical segments (n = 3) during extension. The probe also underwent uniaxial compression in cadaveric facets to evaluate the effect of orientation relative to the contact surface on the probe signal.

Results. Although experimental and theoretical pressure profiles followed the same trends, measured maximum pressures were half of the theoretical ones. In the orientation study, maximum pressures were not different for probe orientations of 0° and 5°, but no signal was recorded at orientations greater than 15°.

Conclusion. This approach to measure pressure was selected to provide a minimally-invasive method to quantify facet joint pressures during clinically relevant applications. Both the position and orientation of the probe are critical factors in monitoring local pressure profiles in this mobile synovial joint.

Key words: facet joint, pressure, spine, transducer. **Spine 2011; 36:1197–1203**

Spinal facet joints transmit load, limit motions, and contribute to pathologies in the spine.[1–3] The local kinematics and kinetics of facet joints are modified by pathology, trauma, and surgical interventions.[4,5] Contact pressure in this spinal joint can provide a readout of modifications to the local mechanical environment of the joint and spine.[6,7] Facet pressures have been indirectly extrapolated from deformations of laminar strain gauges and directly measured by sectioning the facet capsule to implant flat-lying sensors between the articular surfaces.[8–12] While these experimental techniques are valuable to estimate the maximal contact pressures and can localize regions of contact between the joint's articular surfaces, they require cutting the facet capsule. However, capsule resection potentially biases pressure measurements since it can modify the joint's overall mechanical behavior.[13,14] With capsule transection, the facet joint becomes hypermobile that can also induce articular surface contact in nonphysiologic locations. In addition, the presence of film in a joint space has been shown to overestimate contact areas between articular surfaces.[15] Therefore, any approach to measure facet joint contact and pressure while maintaining the natural anatomy of the joint would be advantageous for defining relevant joint biomechanics for spinal loading scenarios.

Cylindrical pressure transducers with a sensing membrane at their tip provide an alternate strategy to access the facet

From the Departments of *Neurosurgery, and †Bioengineering, University of Pennsylvania, Philadelphia, PA.

Acknowledgement date: January 28, 2010. Revision date: May 3, 2010. Acceptance date: June 17, 2010.

The manuscript submitted does not contain information about medical device(s)/drug(s).

Corporate/Industry, Institutional, and Foundation funds were received in support of this work.

Although one or more of the author(s) has/have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this manuscript, benefits will be directed solely to a research fund, foundation, educational institution, or other nonprofit organization which the author(s) has/have been associated.

Address correspondence and reprint requests to Beth A. Winkelstein, PhD, Department of Bioengineering, School of Engineering and Applied Science, University of Pennsylvania, 210 S. 33rd St, Room 240, Skirkanich Hall, Philadelphia, PA; E-mail: winkelst@seas.upenn.edu

DOI: 10.1097/BRS.0b013e3181ee7de2

articulations while sparing the capsular ligament because they can be inserted through the facet bone. Although this class of transducers has been used primarily for aerospace, marine, and automotive applications,[16–18] it was shown to maintain its high accuracy (±0.1%)[16] in a very harsh environment (600°C, 100 psi). Therefore, it offers promise for minimally invasive direct pressure measurements in joints because it can be fitted into a hole. However, because the sensing element is located at the probe's tip, the measured facet contact pressure may depend both on the orientation of the probe and its position relative to the articular surface, as well as the compliance of the material(s) it contacts.

While tip-mounted pressure probes may enable minimally invasive measurement of facet contact pressures, their performance in complicated geometries and loading scenarios like that experienced by the cervical facet joint during spinal loading has not been characterized. Accordingly, complementary studies were performed to investigate potential limitations of using a tip-mounted transducer to measure contact pressures in the cervical facet joint. The XCEL-100–50 psi transducer (Kulite, Leonia, NJ) has a hysteresis and repeatability error (±0.5%) that is on the same order as that of a miniature transducer to monitor intervertebral disc pressure in cadavers.[19] In the first study, the probe's *in situ* precision during sagittal bending was assessed using a surrogate mimicking the human cervical anatomy to compare experimental contact pressures to theoretical values for applied bending. A second study used both the surrogate and cadaveric spinal motion segment specimens to evaluate the spatial pattern of contact between articular surfaces using pressure sensitive paper in the facet joint. Finally, the effect of probe orientation with respect to the joint surface was also evaluated in a separate study using isolated cadaveric facet joints during uniaxial compression to more fully evaluate issues affecting use of this type of probe in this sort of application.

MATERIALS AND METHODS

A cylindrical pressure probe (XCEL-100–50A; Kulite Semiconductor Products; Leonia, NJ) was selected for its small diameter (2.61 mm). The deformation of the strain gauge sensing membrane (diameter of 2.21 mm) at the probe's tip is linearly proportional to applied pressure. The probe interfaces with a data acquisition board featuring a strain gauge card (OM2–8608 backplane, OM2–162 bridgesensor; Omega Engineering; Stamford, CT) in a full Wheatstone bridge configuration. Data from the pressure probe were acquired at 100 Hz using LabVIEW (version 8, National Instruments; Austin, TX).

Surrogate Facet Joint Pressures Measured With Probe During Flexion-Extension Moment

Measuring the facet contact pressure is not straightforward because loading depends on the complex anatomy and local kinematics of the articulating surfaces in the joint. Accordingly, the probe's precision was evaluated in a realistic testing scenario using an anatomic surrogate undergoing flexion and extension. A surrogate cervical motion segment was assembled from synthetic C4/C5 bone models (3B Scientific GmBH; Hamburg, Germany). An analog intervertebral disc was simulated out of rubber cement and the facets' articular surfaces were covered with paraffin to replicate the low coefficient of friction of cartilage. The pressure transducer was secured by press-fitting it in a hole that was drilled in the center of the left C4 pillar with an orientation perpendicular to the articulating surfaces (Figure 1A). The probe was inserted through C4 to contact the articular surface of C5 by crossing the gap in the joint space. Kirschner-wires and Flow Stone (Whip Mix Corp.; Louisville, KY) were used to rigidly fix the C5 vertebra to the stationary base of the mechanical testing machine (Model 5865, Instron; Norwood, MA).

A screw was positioned in the midsagittal plane of the surrogate, extending out of C4 on both the posterior and anterior sides. The downward displacement of the Instron crosshead (Instron; Norwood, MA) was applied at the end of the screw to impose either an extension or flexion moment depending on whether it was coupled to either the posterior or anterior end, respectively (Figure 1). Vertical displacements of 1.5 mm were applied at 0.5 mm/sec for 10 cycles, corresponding to moments of 0.18 Nm in extension and 0.025 Nm in flexion. Each test was repeated three times at one-minute intervals. Such low moments were applied to enable a comparison between the theoretically-expected pressure and the experimental pressure measured by the probe and permitted evaluation of the transducer's resolution. Conservative testing was also selected to preserve the integrity of the probe. Ink marks were placed on the lateral side of the facet pillar edges, laminae, vertebral bodies, probe, and screw (Figure 1A). A charged-coupled device camera with resolution of 704 by 400 pixels (Phantomv4.3, Vision Research; Wayne, NJ) tracked the marks during loading at 60 Hz; the vertical force and displacement of the crosshead (resolution of 0.02 mm)[20] and the probe output were monitored.

The crosshead data and surrogate kinematics were used to calculate the theoretical pressures applied to the probe to compare to the corresponding experimentally measured pressures. The mark positions were tracked using the ProAnalyst software (Xcitex Inc.; Cambridge, MA) to identify the instantaneous axis of rotation (IAR) of C4 relative to C5 in the sagittal plane (point Q in Figure 1). The applied moment (M) was calculated by multiplying the applied force (F) by the corresponding moment arm (e), which is the distance between point Q and the point on the moment arm where the vertical displacement was applied (Figure 1B). Since the applied force and applied moment were resisted by the surrogate as whole, a portion of the reaction moment opposing motion was generated by the rubber cement disc analog because of its intrinsic rotational stiffness. Therefore, the contribution of the synthetic disc was measured and incorporated into the calculation of the reaction force at the facet joint, from the overall force (F) measured by the load cell. The reaction force (F_R) at the contact between the probe and the articular facet surface (point P) was calculated using the applied moment, the sagittal and overall angles of rotation (φ, ψ, ω, respectively) of the C4 facet surface, the rotational stiffness of the

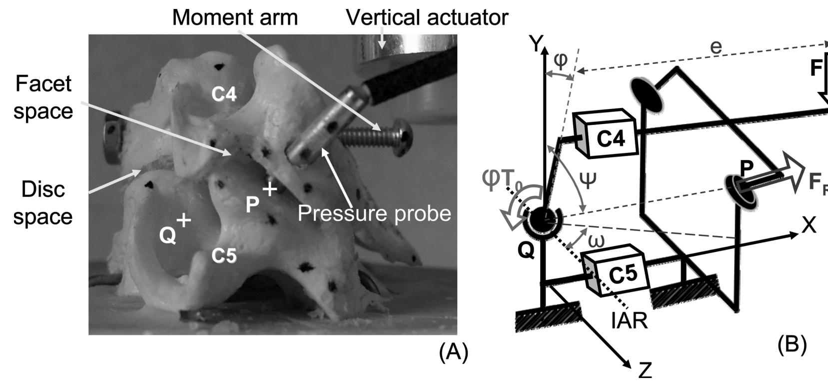

Figure 1. Photograph (**A**) and free-body diagram (**B**) of the C4/C5 cervical spinal unit surrogate in the configuration for applied extension.

rubber cement disc (T_0), and the sagittal coordinates of point P (a, b) in the X-Y plane with origin at point Q (Figure 1B), according to equation {1}.

$$F_R = \frac{M - \phi \mathrm{T}o}{\left(a\cos\psi + b\sin\psi\sin\omega\right)} \qquad (1)$$

The theoretical pressure (Pt) was estimated by dividing the reaction force (F_R) by the average sensing membrane area (3.84 mm^2) according to equation {2}, and the difference between the estimated initial and maximum pressures was taken as the increase in theoretical pressure.

$$P_t = \left(\frac{4F_R}{\pi D^2}\right) \qquad (2)$$

The mean theoretical and experimental pressure increases were compared using a Student *t* test, with significance at *P* less than 0.05.

Facet Joint Contact Pressure Locations Detected by Pressure Paper During Extension

The contact region of both the articular surfaces and the probe location were measured and compared to provide context for the shape and magnitude of the pressure signals detected by the probe. Pressure-sensitive and tracing paper were each used separately to evaluate the location of facet articular contact and the probe tip, respectively, during extension applied to the surrogate and to cadaveric (n = 1 C2/C3; n = 2 C4/C5) spinal motion segments. A similar moment arm as described earlier was used to load the cadaveric spinal motion segments, with a 3.2 mm-diameter screw through the upper vertebral body in the midsagittal plane.

For each case, permanent-ink black dots (0.41 mm diameter) were made along the exposed lateral bony edge of the facet joint, on the surrogate and each cadaveric specimen, to serve as anatomic reference marks. The surrogate and each cadaveric specimen were each positioned in the Instron and pressure-sensitive Fuji paper (Pressurex Zero, 7.2–28 psi; Sensor Products Inc.; Madison, NJ) was inserted in the joint space from the lateral side to measure the magnitude and location of the contact pressure developed between the articular surfaces during extension. Capsule transection was required before inserting pressure-paper in the facet joint of the cadaveric motion segments. The vertical displacement of the Instron crosshead applied to the extremity of a screw was converted to an extension moment of 0.19 Nm for the surrogate and from 0.8 to 1.6 Nm for the cadaveric motion segment specimens, matching moments applied to cervical motion segments reported in the literature.[21–24] The moment was applied and the point of a Kirschner-wire was used to trace the lateral and dorsal facet borders and anatomic reference marks on the Fuji paper while it was still in the joint. The specimen was unloaded and the Fuji paper was carefully removed from the joint space and replaced with a piece of white tracing paper of similar size. Under the same extension moment, the joint contour and, reference marks were again marked on the tracing paper and the probe position was marked by introducing a rigid rod with an inked tip through the hole in the upper lateral mass that previously housed the pressure probe. For analysis, the color density on the Fuji paper was quantified using known calibrated applied pressure magnitudes as per manufacturer instructions. The region(s) of articular contact and probe location were compared for each of the surrogate and cadaveric specimens by matching the pressure-sensitive and tracing papers using their outer edges and reference markings.

Effect of Probe Orientation on Pressure Magnitude with Cadaveric Articular Facets

The dependence of the tip-mounted probe signal on its orientation relative to the articular surface was assessed using a combined set-up with isolated cadaveric facets and fabricated probe housing fixtures. A series of polyethylene rods (19.3 mm long, 15.8 mm diameter) were fabricated with a 2.78 mm diameter hole oriented at 0°, 5°, 15°, 30°, and 45° from the vertical axis. The probe was secured in the hole in the rod by a lateral securing screw. Each rod was affixed to the base of the Instron frame and a cadaveric C5 superior facet (65 year-old male) was affixed to the crosshead with the cartilaginous articular surface oriented horizontally. The facet contacted the tip of the pressure transducer and then displaced vertically downward at 0.05 mm/sec to 0.08 mm for 20 cycles, with continual pressure data acquisition. Three trials were performed for each angle of the probe using each of the right and left facets, separately. The increase in pressure was calculated as described earlier in equation {2}, taking into account the orientation of the reactive force F_R, for the first cycle of each trial. Mean experimental pressure increases were compared between angular orientations using paired *t* tests.

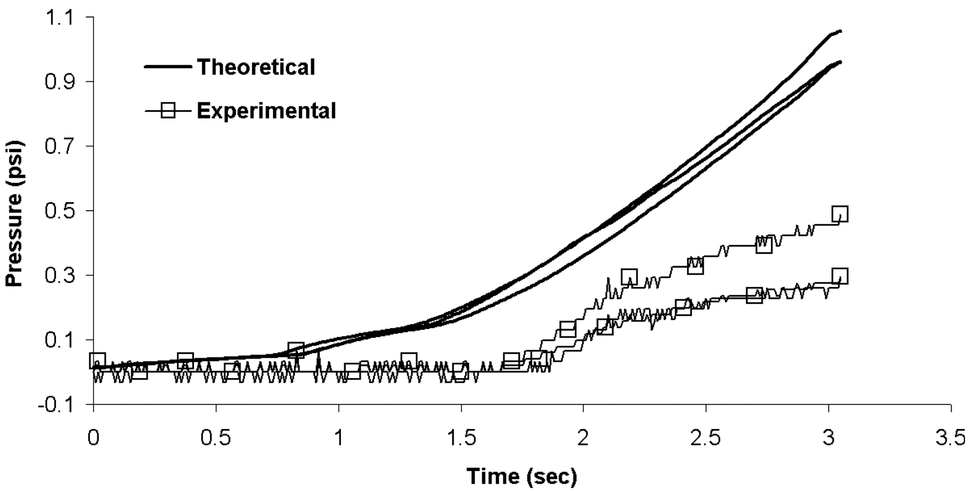

Figure 2. Theoretical (solid) and experimental (❐)pressure increase relative to baseline readings during the loading portion of an extension moment cycle applied to the surrogate motion segment.

RESULTS

Changes in pressure were detected by the probe when a moment was applied in extension but not in flexion. Although the experimental and theoretical pressure profiles exhibited similar shapes, they differed in magnitude and timing (Figure 2). The pressure profiles increased similarly in all extension trials, but the maximum experimental pressure increase was more than two times smaller than that theoretically predicted on average (Figure 2; Table 1), and this difference was significant ($P < 0.01$). The experimental pressure increase was delayed by 1.5 to 2 seconds (corresponding to 0.05–0.08 Nm of extension) compared to the immediate increase in theoretical pressure for extension (Figure 2). In flexion, both the experimental and theoretical pressures were unchanged owing to a lack of contact due to the joint's opening. Video analysis confirmed that the transducer did not move relative to the surrogate during all of the tests.

Comparison of the probe tip location and region(s) of articular joint contact detected by the papers indicated a general mismatch between the probed and contacting areas for both the surrogate and cadaveric segments. The articular surfaces mainly contacted along the most posterior and lateral regions of the facet (Figure 3). For the cadaveric specimens, the area probed by the pressure transducer was located toward the center of the joint (Figure 3A). However, in the surrogate specimen the probe tip was more lateral and partially overlapped with the area of articular contact (Figure 3B).

In the orientation study, pressure was detected only when the probe was oriented largely perpendicular to the applied compression, at the smallest angular orientations (0°, 5°) (Figure 4). When the probe was oriented at an angle of 15° or more off the vertical axis, no pressure was detected (data not shown). The measured pressure ranged between 1.7 and 5.2 psi and between 9.0 and 14.2 psi for the left and right facet, respectively. For the tests on the right facet, the 0° orientation pressure values were smaller than the values at the 5° orientation, but this difference was not significant ($P = 0.06$). For the tests on the left facet, the 0° orientation pressure values were also smaller than at the 5° orientation, and were significantly different ($P = 0.05$).

TABLE 1. Average (±SD) Surrogate Facet Pressure Increase During Maximal Extension for Three Trials (PSI)

	Extension
Theoretical	0.960
	0.959
	1.056
	0.992 (±0.056)
Experimental	0.487
	0.292
	0.292
	0.357 (±0.113)

DISCUSSION

Despite limitations related to the particular transducer used in this work, the results of these studies suggest that the probe technique may have some utility in measuring facet joint pressures during relevant test paradigms. However, several limitations have been identified that merit consideration for future use of this sort of approach. In the surrogate study, the pressure profiles monitored by the probe during bending did not match the theoretical values in magnitude, but did reveal a similarity in the shape of the pressure response (Figure 2 and Figure 3B; Table 1). The smaller maximum values and the delay in the onset of the measured pressure increases may result from the probe position in the joint, the local mechanical environment (Figure 2 and Figure 3), and/or the probe design. Furthermore, the delay in the detection of joint contact pressure in the surrogate may be explained, in part, by the fact that the probe tip becomes engaged only after some initial joint motion has occurred. Because this probe is designed to measure pressure in fluids, it does not actually measure pressure changes until the sensing membrane is deformed, as occurs when contact is made with the opposing articular cartilage surface. The difference in magnitude may be linked to an incomplete engagement of the sensing membrane with the articular surface. In addition, part of the discrepancy could

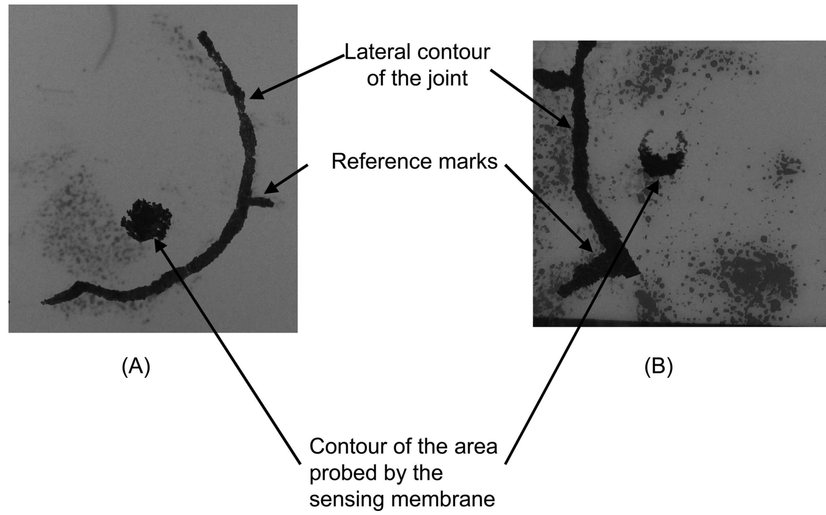

Figure 3. Superimposed contact regions of the probe tip mark (black) superimposed on the pressure-sensitive Fuji paper showing joint contact for each of the C4/C5 cadaveric specimen (**A**) and the surrogate (**B**) after applied extension. The contours tracing the lateral joint line and reference marks are indicated. Also evident are the location of the probe tip (darker imprint) and the contact regions made by the articular surface contacts (lighter gray areas within joint).

also be related to the resolution of the transducer. This hypothesis was supported by the finding that there was only a partial overlap detected between the location of the probe tip on the articular cartilage and the region of articular contact during extension using the Fuji paper (Figure 3B).

The local mechanical environment at the point(s) of contact in the joint can also influence the probe's output. For example, the difference in the experimental pressures measured in the surrogate trials may reflect a settling of the probe tip in the material covering the articular surface. Compliance of this material under sequential testing could have caused the 40% decrease in maximum pressure detected in the second and third trials with the surrogate (Figure 2, Table 1). This discrepancy could also be partially attributed to the probe's angular orientation relative to the contacting surface and influences of that contact orientation on probe outputs (Figure 4).

The extension moment applied to the surrogate was small in comparison to the range of moments applied to the cadaveric motion segments. The discrepancy between the experimental and theoretical pressures obtained at those small moments in the surrogate testing (Figure 2) could likely be much larger for greater moments applied to the surrogate. However, in those cases the divergence could also be affected by response of the materials, which were used to constitute the surrogate. Therefore, the comparison between the theoretical and experimental pressures developed during sagittal bending in the surrogate tests may be considered more meaningful at small moments. Also, the application of these small sagittal moments permitted the evaluation of the repeatability and resolution (0.3 psi) of the pressure transducer (Figure 2).

The mapping of joint surfaces from the Fuji paper study (Figure 3A) is the first to investigate the contact pressure developed in the cervical facet joint during extension in an experimental set-up using human models. In this study, articular contact was found to be concentrated along the posterolateral edges of the facet, which is consistent with findings predicted using finite element modeling of the cervical spine facet joint in extension[25] and reported for the lumbar spine.[26] This same region of articular contact was also monitored for the surrogate motion segment in extension (Figure 3B). Since the surrogate and cadaveric specimens were anatomically similar and exhibited similar rotation responses (1°–3°) in extension, the spatial contact data were considered comparable for this first-pass analysis. These data also further support the fact that the capsular ligament does not play a role in the mechanical behavior of the facet joint in extension owing to its fibers being relaxed, since the two responses were similar. This collection of results (*i.e.*, cadaveric, surrogate, and finite element modeling) supports agreement in the identification of a consistent region of articular contact in the cervical facet joint under extension. Defining the anatomic region of contact is crucial in informing where to position insertion of a tip-mounted pressure transducer particularly when using the capsule-sparing technique that is blind to joint anatomy.

The cervical facet joint is surrounded by soft tissue, including fascia, ligaments, and muscle fibers, which make dissection and identification of its orientation cumbersome. The findings from the pressure and tracing papers (Figure 3) illustrate that the intact capsule does obstruct the direct visualization of the articular surface orientations, preventing any direct validation that the probe is in contact with the articular

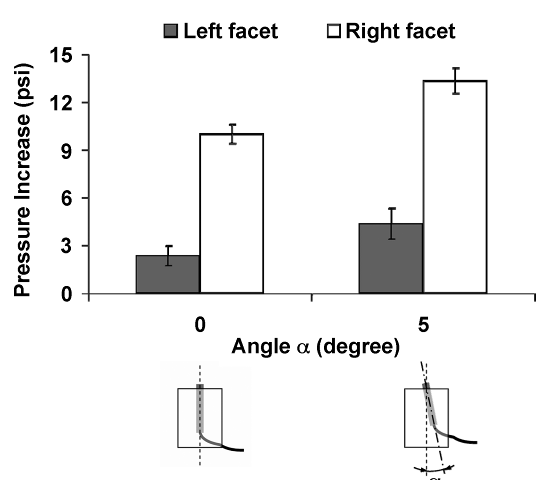

Figure 4. Average (±SD) pressure increase from initial contact with cadaveric articular facet joint surfaces for two orientations (angle α) of the probe relative to the contact surface.

cartilage when inserted in the intact joint. This limitation may prevent the insertion of probes with optimally oriented positions with regard to placement and orientation with respect to the articular surface. However, this issue can be readily circumvented using imaging techniques such as fluoroscopy. This optical method could identify the best location to insert the probe *via* the posterior approach in the rostral pillar and also to clarify the thickness of the facet pillar through which the hole must be drilled. Imaging can also provide information about the general orientation of the joint articulations. Knowing this specific anatomy is imperative for using this type of probe, since it must be inserted perpendicular to the articular surface in order to optimize the measured pressure signal. As demonstrated by the pressure data from the orientation study, this tip-mounted probe is sensitive to its orientation relative to the articular surface (Figure 4). The probe only measured pressure variations in the most vertical orientations when compressed against articular surfaces.

In addition to joint anatomy, the design of the probe and the condition of the cartilage layer can influence the pressure signal. These factors may explain the discrepancy between the pressure magnitudes measured when compressing the left and right facets in the orientation study (Figure 4). The sensing membrane in this type of probe is not located at the very tip of the metallic shaft, but is recessed by 0.25 mm from the end. Therefore, the end of the probe must first penetrate the cartilage layer of the opposite articular surface in order for there to be contact between the cartilage and the sensing membrane. When the probe is 5° off of perpendicular it can penetrate the cartilage layer deeper under compression than when it is completely perpendicular to the articular surface and increase the likelihood for contact with the sensing membrane. However, this design with a recess protects the sensing membrane and can reduce, or even prevent, contact with the opposite surface if the cartilage layer on the opposing surface is too thin. For that case, the metallic end of the probe would actually go through the thin cartilage layer and sit on the subchondral bone, but the thin cartilage layer would be insufficient to engage the sensing membrane. The dependence of the probe's signal on its orientation relative to the articular surface and the reduction of contact caused by the protective recess suggest that this particular probe may not be the most appropriate for this application. The results also indicate that this type of contact measurement should be employed with care in facet joints with deteriorated cartilage layers. Imaging would also help to select specimens that present nondegenerated articular surfaces.

The tip-mounted pressure transducer used in this investigation has an accuracy (±0.1%) and a repeatability (±0.5%)[16,18] similar to other miniature transducers employed to measure intervertebral disc pressure in cadaveric specimens.[19] The accuracy of pressure-sensitive paper films depends on the load applied; Fuji paper is ±15% inaccurate since it over- and underestimates low and high contact pressures by 41% and 5%, respectively.[27] In contrast, the more-expensive and larger TekScan films (TekScan; South Boston, MA) overestimate pressure by up to 4%[27,28] and have a repeatability error of 8%.[10,11,29] Therefore, a tip-mounted pressure transducer offers the possibility for a less invasive and relatively similarly accurate approach to measure facet contact pressure as do pressure films. There is a drawback with using the pressure transducer that was employed in this investigation since it is designed for making measurements in fluids, which makes the output signal highly dependent on the probe position and orientation relative to the articular surface of the facet joint.

Further studies are needed to evaluate and design minimally-invasive orientation independent pressure transducers. Such studies will enable the enhancement and application of this technique in more complicated cadaveric systems where capsular disruption would generate hypermobility or instability of the probed joint, particularly when larger or dynamic loading conditions are applied. Unlike pressure-sensitive film that provides spatial maps of the pressure in the joint,[11,26] a capsule-sparing technique for joint contact pressure provides measurements only at one position, but this can be managed if the probe is positioned where the facet joint contact occurs or in specific regions of interest for particular applications.

The use of this probe technique is repeatable and can offer an easy-to-use, efficient, and adaptable approach to measure temporal pressure profiles in joints without altering their anatomy. However, future studies using this probe technique should more fully evaluate this. A recent pilot study using cadaveric motion segments documented that the extension rotation was not significantly altered by the probe insert and/or capsule transection.[30] Future investigations using this probe technique can provide *in vitro* facet joint contact pressure values that are needed to validate and augment finite element modeling.[31,32] Nonetheless, the findings from these studies identify several factors that influence or limit the performance of pressure measurement in the spinal facet joints. Despite its limitations, a tip-mounted probe does provide continuous, temporal monitoring of the local pressure that can be used without altering the joint's overall mechanical response. Through material improvement and the use of imaging techniques, the factors influencing an objective measurement of the contact pressure in the cervical facet can be appropriately controlled.

➢ Key Points

- ❑ Current methods using pressure-sensitive papers to measure contact pressure in the spinal facet joint require capsulotomy that alters the joints mechanics.
- ❑ A capsule-sparing technique for facet pressure measurement with a tip-mounted probe was evaluated in cadaveric specimens.
- ❑ Probe position and orientation relative to the articular surface, and probe design influence the pressure measurements.
- ❑ Articular surface contact occurs mainly in the posterolateral region of the facet in a cervical spinal motion segment under extension.

Acknowledgments

This project was supported by research funding from Synthes, Inc. and the Catharine Sharpe Foundation and a Research Fellowship from the Neurosurgery Research & Education Foundation.

References

1. el-Bohy AA, Yang KH, King AI. Experimental verification of facet load transmission by direct measurement of facet lamina contact pressure. *J Biomech* 1989;22:931–41.
2. Panjabi MM, Simpson AK, Ivancic PC, et al. Cervical facet joint kinematics during bilateral facet dislocation. *Eur Spine J* 2007;16:1680–8.
3. Winkelstein BA, Nightingale RW, Richardson WJ, et al. The cervical facet capsule and its role in whiplash injury: a biomechanical investigation. *Spine* 2000;25:1238–46.
4. Chang UK, Kim DH, Lee MC, et al. Changes in adjacent-level disc pressure and facet joint force after cervical arthroplasty compared with cervical discectomy and fusion. *J Neurosurg Spine* 2007;7:33–9.
5. Rousseau MA, Bradford DS, Bertagnoli R, et al. Disc arthroplasty design influences intervertebral kinematics and facet forces. *Spine J* 2006;6:258–66.
6. Resnick DK, Watters WC. Lumbar disc arthroplasty: a critical review. *Clin Neurosurg* 2007;54:83–7.
7. Yoganandan N, Pintar FA, Klienberger M. Cervical spine vertebral and facet joint kinematics under whiplash. *J Biomech Eng* 1998;120:305–7.
8. Buttermann GR, Kahmann RD, Lewis JL, et al. An experimental method for measuring force on the spinal facet joint: description and application of the method. *J Biomech Eng* 1991;113:375–86.
9. Hedman TP. A new transducer for facet force measurement in the lumbar spine: benchmark and in vitro test results. *J Biomech* 1992;25:69–80.
10. Niosi CA, Wilson DC, Zhu Q, et al. The effect of dynamic posterior stabilization on facet joint contact forces: an in vitro investigation. *Spine* 2008;33:19–26.
11. Wilson DC, Niosi CA, Zhu QA, et al. Accuracy and repeatability of a new method for measuring facet loads in the lumbar spine. *J Biomech* 2007;39:348–53.
12. Wiseman CM, Lindsey DP, Fredrick AD, et al. The effect of an interspinous process implant on facet loading during extension. *Spine* 2005;30:903–7.
13. Oxland TR, Panjabi MM, Southern EP, et al. An anatomic basis for spinal instability: a porcine trauma model. *J Orthop Res* 1991;9:452–62.
14. Zdeblick TA, Abitbol JJ, Kunz DN, et al. Cervical stability after sequential capsule resection. *Spine* 1993;18:2005–8.
15. Liau JJ, Hu CC, Cheng CK, et al. The influence of inserting a Fuji pressure sensitive film between the tibiofemoral joint of knee prosthesis on actual contact characteristics. *Clin Biomech(Bristol, Avon)* 2001;16:160–6.
16. Kurtz AD, Ned AA, VanDeWeert J, et al. High accuracy miniature pressure transducer. In: *Proceedings of the 53rd International Instrumentation Symposium. Vol 470*. Research Triangle Park, NC: The Instrumentation, Systems, and Automation Society; 2007:303–18.
17. Wang X, Xu J, Zhu Y, et al. Verifying an all fused silica miniature optical fiber tip pressure sensor performance with turbine engine field test. In: *Sensors for Harsh Environments II. Vol 5998*. Boston, MA: Proceedings of SPIE—The International Society for Optical Engineering; 2005.
18. Hurst AM, Kurtz AD, Kochman B. High temperature static and dynamic pressure transducer for combustion instability control using acoustic low-pass filter structures. In: *Proceedings of the ASME Turbo Expo 2008*; June 9–13, 2008; Berlin, Germany:369–80.
19. Cripton PA, Dumas GA, Nolte LP. A minimally disruptive technique for measuring intervertebral disc pressure in vitro: application to the cervical spine. *J Biomech* 2001;34:545–9.
20. Quinn KP, Winkelstein BA. Cervical facet capsular ligament yield defines the threshold for injury and persistent joint-mediated neck pain. *J Biomech* 2007;40(10):2299–306.
21. Moroney SP, Schultz AB, Miller JA, et al. Load-displacement properties of lower cervical spine motion segments. *J Biomech* 1988;21(9):769–79.
22. Oda T, Panjabi MM, Crisco JJ III. Three-dimensional translational movements of the upper cervical spine. *J Spinal Disord* 1991;4(4):411–9.
23. Zhang QH, Teo EC, Ng HW, et al. Finite element analysis of moment-rotation relationships for human cervical spine. *J Biomech* 2006;39(1):189–93.
24. Nightingale RW, Carol Chancey V, Ottaviano D, et al. Flexion and extension structural properties and strengths for male cervical spine segments. *J Biomech* 2007;40(3):535–42.
25. Kumaresan S, Yoganandan N, Pintar FA. Finite element modeling approaches of human cervical spine facet joint capsule. *J Biomech* 1998;31:371–6.
26. Dunlop RB, Adams MA, Hotton WC. Disc space narrowing and the lumbar facet joints. *J Bone Joint Surg Br* 1984;66:706–10.
27. Bachus KN, DeMarco AL, Judd KT, et al. Measuring contact area, force, and pressure for bioengineering applications: using Fuji Film and TekScan systems. *Med Eng Phys* 2006;28:483–8.
28. Fregly BJ, Sawyer WG. Estimation of discretization errors in contact pressure measurements. *J Biomech* 2003;36:609–13.
29. Hoffmann K, Decker K. Inaccuracies in measurement of contact pressure due to the measuring grid of a foil sensor. *Int J*. Int Syst Tech Appl 2007;3(1,2):80–94 .
30. Jaumard NV, Bauman JA, Welch WC, et al. Biomechanical comparison of contact pressure in the cervical facet joint during bending using a probe and pressure-sensitive paper. In: *Proceedings of the ASME 2010 Summer Bioengineering Conference*; June 16–19, 2010; Naples, FL.
31. Ng HW, Teo EC, Lee KK, et al. Finite element analysis of cervical spinal instability under physiologic loading. *J Spinal Disord & Tech* 2003;16:55–65.
32. Schmidt H, Heuer F, Wilke HJ. Interaction between finite helical axes and facet joint forces under combined loading. *Spine* 2008;33:2741–8.