

COA/CORS Combined Paper Session 5: Spine/Trauma •

Moderators Albert J.M. Yee, ON, and Thomas Oxland, BC

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Biomechanical Characterization of Cervical Spine Dislocation in an Innovative Spinal Cord Injury (SCI) Model

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Purpose: Recent studies have shown differences in short term spinal cord pathology between spinal column injury mechanisms, such as contusion and fracture-dislocation. Such differences may exist at longer time points, and thus survival studies are needed in the dislocation models. A more in-depth characterization of the dislocation model is needed for development of a mild-moderate cervical spine dislocation model in a rat that is suitable for survival studies. Specifically, our objective in this study was to determine the dislocation displacement that produces initial spinal column failure in a Sprague-Dawley rat model and to validate a consistent injury at the desired dislocation in-vitro and in-vivo. **Method:** For the dislocation model, the dorsal ligaments and facets at C4-C5 were removed to mimic the type of posterior element fracture and ligament injury commonly seen in a bilateral fracture-dislocation. C3 and C4 were clamped together and held stationary while the clamp holding C5 and C6 was connected to an electromagnetic actuator and displaced dorsally to produce the injury while force and displacement were recorded. Twenty-eight isolated cervical spine specimens of Sprague-Dawley rats were used to determine dislocation displacement at initial spinal column failure. The C4-C5 segment sustained dislocation (>3mm) injury at 0.05mm/s (n=11), 100mm/s (n=4) and 1000mm/s (n=13). Initial spinal column failure was defined as with maximum force during the dislocation. A dislocation displacement of 1.4mm was applied to 7 isolated specimens and 4 anesthetized rats at 430mm/s. The spinal column failure was inspected up to 3 days after injury, as well as hemorrhage of spinal cord in-situ. **Results:** The dislocation displacement at in-vitro spinal column failure was $0.95\text{mm} \pm 0.32$ and not significantly different among specimens at the three dislocation speeds. Under a dislocation displacement of 1.4mm, rupture of the C4-C5 disc occurred in all in-vitro ($0.67\text{mm} \pm 0.38$) and in-vivo ($0.65\text{mm} \pm 0.17$) cases. SCI hemorrhage at epicenter was observed in 3 of 4 cases. **Conclusion:** The initial spinal column failure in an innovative SCI model occurs at displacement between 0.65mm and 0.95mm. Dislocation displacement of 1.4mm results in spinal column failure consistently and SCI hemorrhage, and may be suitable for survival studies.

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Maverick Total Disc Replacement in the Lower Lumbar Spine Adjacent to a Long Spinal Fusion: An In Vitro Biomechanical Study of Kinematics

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Purpose: A long spinal fusion across the thoracolumbar region is sometimes applied in scoliosis. Adjacent level degeneration below these constructs has been documented. Treatment with an artificial disc replacement below the fusion has been proposed to prevent degeneration there. There is currently little data detailing the expected biomechanics of this situation. The objective of this study was to evaluate range of motion (ROM) and helical axis of motion (HAM) changes due to one- and two-level Maverick total disc replacement adjacent to a long spinal fusion. **Method:** A multidirectional flexibility testing protocol with compressive follower preload was used to test seven human cadaveric spine specimens (T8-S1). A continuous pure moment ± 5.0 Nm was applied in flexion-extension (FE), lateral bending (LB) and axial rotation (AR), with a compressive follower preload of 400 N. The motion of each vertebra was monitored with an optoelectronic camera system. The test was completed for the intact condition and after each surgical technique: (1) T8-L4 fusion and facet capsulotomy at L4-L5 and L5-S1; (2) L4-L5 Maverick; (3) L5-S1 Maverick. Maverick total disc replacement and fusion with the CD Horizon system was performed. Repeated measures ANOVA was used to analyze changes in ROM and HAM of the L4-L5 and L5-S1 segments. **Results:** Following L4-L5 Maverick replacement, L4-L5 ROMs tended to decrease slightly (on average from $6.2^\circ \pm 2.8^\circ$ to $5.1^\circ \pm 3.8^\circ$ in FE, $1.1^\circ \pm 1.1^\circ$ to $0.9^\circ \pm 0.5^\circ$ in LB and $1.3^\circ \pm 0.9^\circ$ to $1.0^\circ \pm 0.6^\circ$ in AR). With two-level Maverick implantation, L5-S1 ROMs tended to increase slightly in FE (from $6.6^\circ \pm 2.6^\circ$ to $7.1^\circ \pm 3.9^\circ$), and to decrease slightly in LB (from $1.5^\circ \pm 0.9^\circ$ to $1.0^\circ \pm 0.3^\circ$) and AR (from $1.5^\circ \pm 1.5^\circ$ to $1.1^\circ \pm 0.6^\circ$), compared to the fused condition. As a trend, HAM location shifted posteriorly in FE and AR, and inferiorly in LB following Maverick replacement. However, neither ROM nor HAM at these two segments showed any significant change due to the implantation of one- or two-level Maverick total disc replacement in any of the three directions. **Conclusion:** The present results suggested that lower lumbar segments with Maverick disc replacement exhibited intact-like kinematics in both extent and quality of motion.

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Cervical Spinal Motion that would Otherwise be Safe, Can Cause Spinal Cord Compression in a Stenotic Spine

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Purpose: The average age of people suffering spinal cord injuries in many countries is shifting toward an older population, with a disproportionate number occurring in the spondylotic cervical spine. These injuries are typically due to low energy impacts, such as a fall from standing height. Since a stenotic spinal canal (a common feature of a spondylotic cervical spine) can cause myelopathy when the spine is flexed or extended, traumatic flexion or extension likely causes the injury during the low energy impact. However, this injury mechanism has not been observed experimentally. **Method:** To better understand this injury mechanism an in-vitro study, using six whole cervical porcine spines, was conducted. The

following techniques were combined to directly observe spinal cord compression in a stenotic spine during physiologic and super-physiologic motion:• A radio-opaque surrogate cord, with material properties matched to in-vivo specimens, replaced the real spinal cord.• Sagittal plane X-rays imaged the surrogate cord in the spine during testing.• Varying levels of canal stenosis were simulated by a M8 machine cap screw that entered the canal from the anterior by drilling through the C5 vertebral body.• Pure moment loading and a compressive follower load were used to replicate physiologic and super-physiologic motion. **Results:** Initial results show that a stenotic occlusion that removes all extra space in the canal in the neutral posture, without compressing the cord, can lead to spinal cord compression within physiologic ranges of flexion and extension. The spinal cord can also be compressed during slightly super-physiologic flexion and extension with only 25% canal occlusion. Physiologic loads and motions in the same spines did not cause cord compression when canal occlusion was 0%. **Conclusion:** These results support the hypothesis that cervical spinal canal stenosis increases the risk of spinal cord injury because spinal cord compression was observed during motions and loads that would be safe for a non-stenotic spine. These results are limited primarily due to the use of a porcine spine. However, this new stenosis model and experimental technique will be applied to in-vitro human spine specimens in future work.

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The Positive Effects of Poly-N-acetyl Glucosamine on Human Intervertebral Disc Cell Metabolism in Vitro

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Purpose: There is interest in biologic strategies that can potentially treat degenerative disc disease (DDD). A new deacetylated derivative of a marine diatomic glycosaminoglycan (DEAC) was developed and incorporated into two sulphated hydrogel formulations; Gel 1 and 2. These materials were proposed to have a reparative effect on damaged tissue. Biochemical studies were conducted using primary human disc cell (HDC) cultures. **Method:** HDCs were isolated from surgical specimens by sequential enzymatic digestion (pronase and collagenase). Time-course in-vitro studies were conducted on cell cultures treated with DEAC, Gel 1 or Gel 2 (28 day period). Proteoglycan content (alcian blue), cellular viability/proliferation (MTT assay), and type collagen II, aggrecan expression (RT-PCR, immunohistochemistry) was assessed. **Results:** When compared to controls, the DEAC, Gel 1 and 2 treated HDC groups showed significant increases in proteoglycan content as early as day 12. The greatest effect was observed with Gel 1 (78.4±1.9 fold greater optical density compared to control, $p < 0.05$). The amount of proteoglycan quantified on DEAC treated

HDCs on day 28 was 27.7 ± 0.09 times higher than control ($p < 0.05$). MTT results demonstrated that Gel 1 group showed the highest viability over the study period (mean optical density 0.13 ± 0.01 versus 0.039 ± 0.01 in controls). There were no significant differences in cell proliferation of Gel 2, DEAC and untreated control groups. RT-PCR and immunohistochemistry demonstrated expression of type II collagen and aggrecan consistent with the disc phenotype. **Conclusion:** The results of this study demonstrates that formulations derived from poly-N-acetyl glucosamine (pGlcNAc) have positive effects of disc cell metabolism as quantified by proteoglycan content, cellular viability and proliferation, and the expression of key extra-cellular matrix molecules. The sulphated formulation of deacetylated pGlcNAc (Gel 1) appeared to have the greatest in-vitro effect followed by DEAC and the short fiber construct of Gel 2. It is possible that the pGlcNAc fibers in Gel 2 were not as soluble to the extent of DEAC due to their inability to form strong hydrogen bonds. This study shows promise towards ongoing evaluation of novel biomaterials for the potential DDD treatment through tissue regenerative or reparative schemes.

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Stabilization of the Posteromedial Fragment in Bicondylar Tibial Plateau Fractures

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Purpose: To compare locking and non-locking single and dual plating constructs in maintaining posteromedial fragment reduction in a bicondylar tibial plateau fracture model. We hypothesized that posteromedial fragment fixation with medial and lateral non-locked constructs would tolerate higher loads than lateral locked constructs alone. **Method:** Thirty adult-sized composite tibiae were identically fractured into an AO 41-C1.3 pattern. Six plate constructs were tested: (1) lateral 8-hole 3.5 mm conventional non-locking proximal tibial plate [CP]; (2) CP + posteromedial 6 hole 3.5 mm limited contact dynamic compression plate [CP + LCDCP]; (3) CP + posteromedial 6 hole 1/3 tubular plate [CP + 1/3 tubular]; (4) 8-hole 3.5mm Proximal Tibial Locking plate [PTLP]; (5) 8-hole 3.5 mm LCP (locking compression plate) proximal tibia plate [LCP]; (6) 9-hole Less Invasive Stabilization System [LISS] plate. Specimens were cyclically loaded to failure or a maximum load of 4000N. Load at posteromedial fragment failure was recorded. **Results:** Fragment failure occurred at the posteromedial fragment first. The CP + 1/3 tubular construct had the highest average load to failure (3040 N). In two instances, the CP + 1/3 tubular construct did not fail under the highest loads applied and was the only construct to have specimens that did not fail by 4000 N. The CP + 1/3 tubular plating construct demonstrated significantly higher load at failure compared with the PTLP ($p=0.036$), the LCP ($p=0.004$), and the LISS ($p=0.012$). The CP + 1/3 tubular group did not demonstrate a significant difference in load at failure when compared with the CP ($p=0.093$) or the CP + LCDCP ($p=0.108$). The LISS demonstrated a significantly higher load at failure compared to the LCP ($p=0.046$) but not to the PTLP ($p=0.800$). **Conclusion:** The posteromedial fragment tolerated

higher loads with the CP + 1/3 tubular plate construct. The superiority of the dual plate construct may in part be due to the unreliable penetrance of the posteromedial fragment by the laterally applied locking screws.

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An Automated Micro-CT Based Quantitative Analysis of Healthy and Metastatically Involved Vertebral Architecture

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Purpose: The objective of this study is to develop and utilize a highly automated microCT based analysis tool to quantify microstructural differences in bone due to metastatic involvement in whole rat vertebrae. **Method:** First and Third lumbar vertebrae from healthy (n=4) and metastatically involved (n=4) rnu/rnu rats were excised for analysis (total of 8 vertebrae). Lytic metastases were developed via intracardiac injection of MT1 human breast cancer cells. The specimens were scanned using microCT at 17.5 microns isotropic resolution. A highly automated algorithm was developed for whole vertebral segmentation based on the microCT data, including the posterior elements (AmiraDev3.1). This was accomplished using an atlas-based method incorporating demons deformable registration followed by refinement through level set curvature evolution. Volumetric concurrency was used to compare segmentations generated by the automated algorithm to manually refined segmentations. The segmentations were up-sampled by 4 and edge-enhanced and further segmented using a thresholding technique to have a clear segmentation of the individual trabeculae without advancing into the bone marrow (AmiraDev3.1). The cortical shell was removed automatically before analyzing the trabecular structure. Cortical bone volume (CBV) was calculated by subtracting the volume of the full segmentation from the segmentation with no cortical shell. The interior segmentation was then used to calculate Trabecular Bone Volume (TBV), Trabecular Thickness (TbTh), Trabecular Separation (TbSp), Trabecular Number (TbN) based on the expressions described by Parfitt, et al (1983). Finally mean intercept length (MIL) was used to calculate the anisotropy of the trabecular tissue. Analysis were carried out on both the healthy and metastatically involved vertebrae. **Results:** The automated algorithm including the level set method refinement produced good tracking of the boundaries of entire rat vertebrae. Consistent results yielded significant reduction in TBV, slight reduction in TbN and TbTh, and significant increase in TbS in metastatic vertebrae compared to healthy. No significant differences were observed in CBV. The metastatic vertebrae was also found to be significantly more anisotropic than the healthy group. **Conclusion:** The accuracy of the highly automated algorithm developed in this study to analyze microstructure in whole rat vertebrae make it a suitable tool for further analyzing the effects of existing and new treatments for spinal metastases at a preclinical level.

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Quantification of Pronator Quadratus Contribution to Isometric Pronation Torque of the Forearm

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Purpose: Open reduction internal fixation with a volar plate is a popular surgical option for distal radius fractures. The pronator quadratus (PQ) must be stripped from the distal radius in this procedure. PQ is an important pronator of the forearm and stabilizer of the distal radioulnar joint. The purpose of this study was to investigate pronation torque in healthy volunteers before and after temporary paralysis of the PQ with lidocaine under EMG guidance. **Method:** A custom-made apparatus was built to allow isometric testing of pronation torque at 5 positions of rotation: 90° of supination, 45° of supination, neutral, 45° of pronation and 80° of pronation. It was validated using a test-retest design with 10 subjects. For the study, 17 (9 male, 8 female) right hand dominant volunteers were recruited. They were tested at all 5 positions in random order and then had their PQs paralyzed with lidocaine. Repeat testing was performed in the same random order 30 minutes after injection. Three subjects underwent unblinded testing with saline injected instead of lidocaine. **Results:** After paralysis of PQ with lidocaine, pronation torque decreased by 23.2% ($p=0.0010$) at 90° of supination, 16.7% ($p=0.0001$) at 45° of supination, 22.9% ($p=0.0002$) in the neutral position, 20.4% ($p=0.0066$) at 45° of pronation and 22.2% ($p=0.0754$) at 80° of pronation. All were statistically significant except 80° of pronation. Peak torque values before and after injection were highest in the supinated positions (8.2 Nm at 45° supination) and decreased gradually as the subjects were in more pronated positions (1.8 Nm at 80° pronation). The test-retest trial demonstrated no evidence of fatigue with repeated testing. The subjects who underwent injection of saline demonstrated no evidence of pronation torque loss secondary to pain or a pressure effect of the injectate. **Conclusion:** This study demonstrated a significant decrease in pronation torque with controlled elimination of PQ function. Open reduction internal fixation of distal radius fractures damages the PQ. This may result in a pronation torque deficit. Functional significance of this loss should be shown. Pronation torque measurement may add to postoperative outcome analysis of surgical procedures about the wrist.

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Biomechanical Analysis of Proximal Humeral Fixation Using Locking Plate Fixation with an Intramedullary Fibular Allograft

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Purpose: The purpose of this study is to compare two fixation methods for surgical neck proximal humeral fractures with medial calcar comminution: 1) locking plate fixation alone and 2) locking plate fixation with intramedullary allograft fibular bone peg augmentation. **Method:** Eight embalmed pairs of

cadaveric specimens were utilized in this study. Dual energy X-ray absorptiometry (DXA) scans were initially performed to determine the bone density of the specimens. Surgical neck proximal humerus fractures were simulated in these specimens by creating a 1-centimeter wedge-shaped osteotomy at the level of the surgical neck to simulate medial calcar fracture comminution. Each pair of specimens had one arm randomly repaired with locking plate fixation, and the other arm repaired with locking plate fixation augmented with an intramedullary fibular autograft bone peg. The constructs were tested in bending to determine the failure loads, and initial stiffness using Digital Imaging Correlation (DIC) technology. The moment created by the rotator cuff was replicated by fixating the humeral head, and applying a point load to the distal humerus. A load was applied with a displacement rate of 4 mm/min, and was stopped approximately every 5 lbs to take a picture and record the load. This process was continued until failure of the specimens was obtained. **Results:** The intramedullary bone peg autograft increased the failure load of the constructs by 1.57 ± 0.59 times ($p = 0.026$). Initial stiffness of the construct was also increased 3.13 ± 2.10 times ($p = 0.0079$) with use of the bone peg. **Conclusion:** The stronger and stiffer construct provided by the addition of an intramedullary fibular allograft bone peg to locking plate fixation may help maintain reduction, and reduce the risk of fixation failure in surgical neck proximal humerus fractures with medial comminution.

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Indomethacin: Shedding New Light on Compartment Syndrome

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Purpose: Indomethacin may preserve tissue viability in compartment syndrome. The mechanism of improved tissue viability is unclear, but the anti-inflammatory effects may alter the relative contribution of tissue necrosis versus apoptosis to cellular injury. Existing studies have only considered indomethacin administration prior to induction of compartment syndrome. The purpose of this study was to determine the effect of timing of indomethacin administration on muscle damage in compartment syndrome, and to assess apoptosis as a cause of tissue demise. **Method:** Twenty-four Wistar rats were randomized to elevated intracompartmental pressure (EICP) for either 45 or 90 minutes (30mm Hg). In the 45 min group, indomethacin was withheld (group 1), given prior to induction of EICP (group 2) or given 15 min prior to fasciotomy (group 3). In the 90 min group, indomethacin was withheld (group 4) or provided 30 or 60 minutes prior to fasciotomy (groups 5 and 6). Intravital microscopy and histochemical staining assessed capillary perfusion, cell damage and inflammatory activation within EDL muscle. Apoptosis was assessed using ELISA staining for caspase-3. Groups were compared with one-way ANOVA ($p < 0.05$). **Results:** Perfusion improved in indomethacin-treated groups. Nonperfused capillaries decreased from group 1 (50.1 ± 2.5), to groups 2 (38.4 ± 1.8) and 3

(14.13±1.73)(p< 0.0001). Similarly, groups 5 and 6 had 25% fewer non-perfused capillaries compared to group 4 (p< 0.0001). Tissue viability improved in indomethacin-treated groups. Groups 2 and 3 showed fewer damaged cells (1±0.5% and 8.7±2%) compared to group 1 (20±14%)(p<0.0001). Groups 5 and 6 showed decreased cell damage (13±1% and 11±1%) compared to group 4 (18±1%) (p<0.01). Apoptotic activity was present in compartment syndrome. At 30 minutes there were elevated caspase levels in EICP groups (0.47±0.08) compared to controls (0.19±0.02). However, indomethacin treated groups did not differ from controls with regards to caspase levels (p>0.05). **Conclusion:** Indomethacin decreased cell damage and improved perfusion in compartment syndrome. The benefits of indomethacin were partially time dependent; some improvement in tissue viability occurred regardless of timing of administration. Although apoptosis was common in compartment syndrome, the protective effect of indomethacin does not appear to be related to apoptosis.