CORS Paper Session 3: Mechanics and Materials ●
Moderators JD Johnson, SK, and Cari Whyne, ON

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Examination of Radiographic Features and Lurch; A Measure of Asymmetric Gait, Among Patients Awaiting Total Hip Arthroplasty
Kyle A. R. Kemp, Dalhousie University; Michael J. Dunbar, Dalhousie University; Lori A. Livingston, Dalhousie University; Allan Hennigar, Dalhousie University

Purpose: Despite their inclusion within clinical practice, standardized radiographs may not accurately project an individual's level of function and mobility. The purpose of this study is to examine the potential relationship between established radiographic features and lurch; a functional measure of asymmetric gait, in a group of patients who will receive total hip arthroplasty (THA). **Method:** Thirty-two patients (16 females, 16 males) identified as hip replacement candidates were recruited, with a mean age of 57.0 years. Lurch was obtained using the Walkabout Portable Gait Monitor (WPGM); a wireless, tri-axial accelerometry device. The independent variables were comprised of the Kellgren-Lawrence Scale, and a collection of standard radiographic features, as adopted by the American Academy of Orthopaedic Surgeons (AAOS), the National Institutes of Health (NIH), and the World Health Organization (WHO). Radiographs were blinded, and the surgeon completing the rating scale was unaware of patient's lurch values. Age-adjusted regression analyses were used to examine the potential association between each radiographic feature and lurch. **Results:** Increased amounts of lurch (i.e. functional impairment) were independently associated with higher Kellgren-Lawrence Scale scores (p=.047), increased Joint Space Narrowing in the mid-portion of the joint (zone 2; p=.004), the presence of acetabular wear (p=.045), an increased severity of subchondral femoral head cysts (p=.004), and higher surgeon-rated Visual Analog Scale scores for overall severity of joint degeneration (p=.008). Lurch was not significantly associated with the remaining 10 features which were examined. Further analyses revealed that lurch was not significantly associated with certain demographic factors, including sex, Body Mass Index, and co-morbid health conditions. **Conclusion:** Although the Kellgren-Lawrence scale was associated with an objective measure of gait, our results indicate that other radiographic features may provide a more accurate prediction of gait performance among this patient population. As lurch appears to be a robust objective measure of physical impairment, which is unaffected by BMI and co-morbidities, we believe that portable triaxial accelerometers can likely be used to conveniently collect objective gait data. This functional data may be used to supplement clinical efforts to screen and prioritize appropriate hip arthroplasty patients.

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Motion-based Joint Coordinate Systems for the Elbow: A New Method for Reducing Variability of Flexion Kinematics

Louis M. Ferreira, University of Western Ontario; Graham J.W. King, St. Joseph's Health Care; James A. Johnson, University of Western Ontario

Results: Repeatability of creating motion-based JCS was less than 1 mm and 1º in all directions. The inter-specimen standard-deviations of position and orientation measurements were smaller for the motion-based than for the anatomy-based JCS in every direction and for every specimen ($p<0.006$). The ulno-humeral varus angle and internal/external rotation kinematics of active flexion showed less inter-specimen variability when calculated using motion-based JCS ($p<0.05$).

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Clinical Procedure for the Measurement of Dynamic Joint Motion - Experimental Validation of the RSPA Technique

Petar Seslija, The University of Western Ontario; Xunhua Yuan, The University of Western Ontario; Douglas Naudie, The University of Western Ontario; Terry M. Peters, The University of Western Ontario; Robert B. Bourne, The University of Western Ontario; Steven J.M. MacDonald, The University of Western Ontario; David W. Holdsworth, The University of Western Ontario

Purpose: Accurate measurement of dynamic joint motion remains a clinical challenge. To address this problem, we have developed a low-dose clinical procedure using the Roentgen Single-plane Photogrammetric Analysis (RSPA) technique. A validation study was performed in a clinical setting, using a conventional digital flat-panel radiography system. **Method:** To validate the technique, three experiments were performed: assessment of static accuracy, dynamic repeatability and measurement of effective dose. A knee joint phantom, imbedded with tantalum markers, was utilized for the experiments. Relative spatial positions of the markers were reconstructed using Radiostereometric Analysis (RSA). A digital flat-panel radiography system was used for image acquisition, and the three-dimensional pose of each segment was determined from single-plane projections by applying the RSPA technique. All images were processed using software developed in-house. To assess static accuracy, the phantom was mounted onto a three-axis translational stage and moved through a series of displacements ranging from 0 to 500 μm. Images of the phantom were acquired at each position. Accuracy was calculated by analyzing differences between reconstructed and applied displacements. To assess dynamic repeatability, the phantom was mounted on a six-axis robot, programmed to apply a flexion-extension movement to the joint. Multiple cine acquisitions of the moving phantom were acquired (30 fps, 4 ms exposure). Repeatability was calculated by analyzing the variation between motions reconstructed from repeated acquisitions.The effective dose of the procedure was measured using an ion-chamber dosimeter. The ion chamber was positioned between the phantom and x-ray source, facing the source. Entrance exposure was measured for multiple acquisitions, from which the effective dose was calculated. **Results:** The accuracy determined from the static assessment was 25 μm and 450μm at the 95% confidence intervals for translations

parallel and orthogonal to the image plane, respectively. Repeatability of the motion reconstructed from dynamic acquisitions was better than ± 200 µm for translations and ± 0.1 for rotations. The average effective dose for a 6 second dynamic acquisition was approximately 2µSv. **Conclusion:** The proposed clinical procedure demonstrates both a high degree of accuracy and repeatability, and delivers a low effective dose.

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Oxidative Stress Markers in the Blood of Patients with Articular Surface Replacement

John Antoniou, McGill University; Fackson Mwale, McGill University; David J. Zukor, McGill University; Olga L. Huk, McGill University; **Alain Petit,** Lady Davis Institute

Purpose: The presence of metal ions in the blood of patients with a metal-on-metal (MM) bearing points to the importance of understanding the long-term effects of these ions. Metal ions have the potential to induce the production of reactive oxygen species (ROS), making them prime suspects for inducing molecular damage in circulating cells. The aim of this study was to analyze the levels of oxidative stress markers in the plasma of patients with hip surface replacement. **Method:** Blood was collected up to 3 years after implantation from 66 patients with articular surface replacement (ASRÔ, DePuy Orthopaedics) and 54 patients with 36 mm-head MM THA. Forty (40) pre-operative patients were also assessed as control group. Total antioxidant levels were measured by the Oxford Biomedical total antioxidant power assay (Oxford, MI) to obtain an overview of the defense capacity of patient's oxidative stress. Peroxide concentrations were measured by the Biomedica OxyStat assay (Medicorp, Montreal, QC) to quantify damage to lipids in the systemic circulation. Nitrototyrosine levels were quantified using the BIOXYTECH® Nitrotyrosine-EIA assay (OxisResearch™, Portland OR) to measure damage to proteins. The concentrations of metal ions were analyzed by inductively coupled plasma-mass spectroscopy. **Results:** Results showed that there were no statistical differences in the concentrations of total antioxidants, lipid peroxides, and protein nitrotyrosines between the control, the ASR, and the 36 mm-head groups. Furthermore, there was no correlation between the concentrations of these markers and the concentrations of both Co and Cr ions (r2 £ 0.006). **Conclusion:** The single most significant obstacle preventing a broader application of metal-on-metal hip arthroplasties and resurfacings continues to be the concerns regarding elevated metal ion levels in the blood and urine of patients. The present results showed that there were no changes in the levels of oxidative stress markers in patients with MM bearings compared to the control group. Given the possible latency periods related to metal ion exposure, longer follow-ups are required to conclusively determine the effects of elevated circulating ions on oxidative stress in the blood of patients with MM bearings.

23 –Image-based Navigation Improves the Positioning of the Humeral Component in Total Elbow Arthroplasty

Colin P. McDonald, St. Joseph's Health Care London; James A. Johnson, St. Joseph's Health Care London; Terry M. Peters, Robarts Research Institute; Graham J.W. King, St. Joseph's Health Care London

Purpose: This study evaluated the accuracy of humeral component alignment in total elbow arthroplasty. An image-based navigated approach was compared against a conventional non-navigated technique. We hypothesized that an image-based navigation system would improve humeral component positioning, with navigational errors less than or approaching 2.0mm and 2.0°. **Method:** Eleven cadaveric distal humeri were imaged using a CT scanner, from which 3D surface models were reconstructed. Non-navigated humeral component implantation was based on a visual estimation of the flexion-extension (FE) axis on the medial and lateral aspects of the distal humerus, followed by standard instrumentation and positioning of a commercial prosthesis by an experienced surgeon. Positioning was based on the estimated FE axis and surgeon judgment. The stem length was reduced by 75% to evaluate the navigation system independent of implant design constraints. For navigated alignment, the implant was aligned with the FE axis of the CT surface model, which was registered to landmarks of the physical humerus using the iterative closest point algorithm. Navigated implant positioning was based on aligning a 3D computer model calibrated to the implant with a 3D model registered to the distal humerus. Each alignment technique was repeated for a bone loss scenario where distal landmarks were not available for FE axis identification. **Results:** Implant alignment error was significantly lower using navigation ($P<0.001$). Navigated implant alignment error was 1.2±0.3 mm in translation and 1.3±0.3° in rotation for the intact scenario, and 1.1±0.5 mm and 2.0±1.3° for the bone loss scenario. Non-navigated alignment error was 3.1±1.3 mm and 5.0±3.8° for the intact scenario, and 3.0±1.6 mm and 12.2±3.3° for the bone loss scenario. Without navigation, 5 implants were aligned outside 5° for intact bone while 9 were aligned outside 10° for the bone loss scenario. **Conclusion:** Image-based navigation improved the accuracy of humeral component placement to less than 2.0 mm and 2.0°. Further, outliers in implant positioning were reduced using image-based navigation, particularly in the presence of bone loss. Implant malalignment may well increase the likelihood of early implant wear, instability and loosening. It is likely that improved implant positioning will lead to fewer implant related complications and greater prosthesis longevity.

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Lysozyme Can Be Chemically Bound to Titanium: Results of a Wet-chemical Functionalization Technique

Dan Padmos, Dalhousie University; Peng Zhang, Dalhousie University; Michael J. Dunbar, Dalhousie University

Purpose: Component loosening is a leading cause of joint replacement failure. Modifying titanium surfaces with chemically bound functional proteins, such as bone morphogenetic protein (BMP), can efficiently strengthen the interface between prosthesis and bone. A prototype system

was developed by using gold nanoparticles (AuNPs) to bridge lysozyme (compositionally similar to BMP) and titanium. **Method:** For reference, lysozyme-conjugated gold nanoparticles (Lys-AuNPs) were prepared in solution via two different pathways: (i) gold compound was reduced in the presence of lysozyme to form Lys-AuNPs or (ii) citrate-stabilized AuNPs were functionalized with mercaptopropionic acid (MPA) to produce carboxylic acid terminated AuNPs which were mixed with lysozyme. Both solutions were characterized with transmission electron microscopy, ultraviolet-visible spectroscopy, circular dichroism spectroscopy (CD), and enzymatic assays. Next, AuNPs were prepared on 99.5% titanium foil discs (n=32) through electroless deposition. Deposition parameters were modified to create two groups of discs with different average diameters of AuNPs, measured by scanning electron microscopy. Some discs from both groups also underwent treatment with MPA. All discs were treated with lysozyme and the adsorbed amounts and activities of lysozyme were examined with micro BCA and enzymatic assays. **Results:** Lysozyme and AuNPs can be conjugated in solution via two different pathways. CD results showed a significant change in the secondary structure of the lysozyme and decrease in enzymatic activity when directly conjugated to AuNPs; however, little change in secondary structure and enzymatic activity was observed for the lysozyme with MPA functionalized AuNPs. For the AuNPs on the titanium discs, SEM showed that the two groups had significantly different average AuNP diameters. Bioactive lysozyme was immobilized onto the discs and the results suggested that discs with the largest AuNPs treated with MPA had higher adsorption and activity of lysozyme. **Conclusion:** A wet-chemical technique may be used to bind lysozyme to titanium via gold nanoparticles. Additionally, it was possible to control the size of the AuNPs on titanium which provides a good platform for further functionalisation with thiol molecules such as MPA. This technique holds promise for binding more functional molecules to surgical implants, hence creating “smart” implants that react to their local environment.

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A Novel Technique for Quantifying Three-dimensional Meniscal Strain

Maeghan Innes, University of Guelph; Craig E. Tschirhart, University of Guelph; David D. McErlain, University of Western Ontario; David W. Holdsworth, University of Western Ontario; Karen D. Gordon, University of Guelph; Mark Hurtig, University of Guelph

Purpose: The mechanical function and strain behavior of the knee meniscus is not fully understood, due to multiple tissues with disparate properties, as well as complex contact patterns and intricate loading mechanisms. More comprehensive understanding of joint mechanics may contribute to improved treatment options for patients with injuries and osteoarthritis. There is very limited information available on the 3D strain of the intact meniscus. The objective of this work was to use mCT with copper microsphere markers to quantify three-dimensional strain of the meniscus under physiologic loading. **Method:** Two healthy fresh frozen ovine knee specimens were harvested. Copper microspheres (0.5mm) were injected into anterior and posterior

tetrahedral clusters in the medial meniscus using 20-gauge hypodermic needles. Needle cavities were sealed with ovine tendon tissue. Joints were loaded to 100% body weight in a 4 DOF CT-compatible pneumatically-driven device with flexion angles ranging from 62-98°. Images were acquired with an eXplore Locus Ultra mCT scanner and reconstructed with commercial software. A time series of images were acquired with the joint unloaded, during static loading, and at a reduced load (25% BW). **Results:** The average maximum principle strains in the anterior element of the two specimens at 62o of flexion increased by 21% during loading and decreased by 13% during unloading. The maximum principle strains were 28% larger in the anterior element than the posterior. The strains in the anterior element decreased by 6.5% with time following load application, and decreased by 16% with load reduction, yielding relatively low residual strain. Strains were 2% larger in the anterior portion with larger flexion angles. **Conclusion:** The objective of this work was to develop a reliable method for quantifying 3D strains in the meniscus. Results support the notion that mCT imaging with copper microspheres in the meniscus may be a viable technique for more comprehensive 3D strain analysis. The relatively low residual strains measured in this study indicate that copper microspheres are stable markers in this application. This technique may be useful in directing future studies aimed at understanding the impact of meniscal pathologies and the success of repair techniques.

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The Effect of Stem Length on the Alignment of the Humeral Component in Computer-assisted Total Elbow Arthroplasty

Colin P. McDonald, St. Joseph's Health Care London; James A. Johnson, St. Joseph's Health Care London; Terry M. Peters, Robarts Research Institute; Graham J.W. King, St. Joseph's Health Care London

Purpose: While computer-assisted techniques can improve the alignment of the implant articulation with the native structure, stem abutment in the intramedullary canal may impede achievement of this alignment. In the current study, the effect of a fixed valgus (6 degree) stemmed humeral component on the alignment of navigated total elbow arthroplasty was investigated. Our hypothesis was that implantation of a humeral component with a reduced stem length would be more accurate than implantation of the humeral component with a standard length stem. **Method:** Thirteen cadaveric distal humeri were imaged using a CT scanner, and a 3D surface model was reconstructed from each scan. Implantation was performed using two implant configurations. The first set was unmodified (Regular) while the second set was modified by reducing the length of the humeral stem to 25% of the original stem (Reduced). A surface model of the humeral component was aligned with the flexion-extension (FE) axis of the CT-based surface model, which was registered to the landmarks of the physical humerus using the iterative closest point algorithm. Navigated implant positioning was based on aligning a 3D computer model calibrated to the implant with a 3D model registered to the distal humerus. **Results:** Implant alignment error was significantly lower for the Reduced implant, averaging 1.3±0.5 mm in

translation and 1.2±0.4° in rotation, compared with 1.9±1.1 mm and 3.6±2.1° for the Regular implant. Abutment of the implant stem with the medullary canal of the humerus prevented optimal alignment of the Regular humeral component as only four of the 13 implantations were aligned to within 2.0° using navigation. **Conclusion:** These results demonstrate that a humeral component with a fixed valgus angulation cannot be accurately positioned in a consistent fashion within the medullary canal of the distal humerus without sacrificing alignment of the FE axis due to stem abutment. Improved accuracy of implant placement can be achieved by introducing a family of humeral components, with three valgus angulations of 0°, 4° and 8°. Based on humeral morphology for these specimens, 12 of the 13 implants may be positioned to within 2° of the native FE axis using one of these 3 valgus angulations.

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CT Based Analysis of Weight Bearing Areas in the Native Acetabulum

Omri Lubocsky, Sunnybrook Health and Science Center, Toronto; Michael R. Hardisty, Sunnybrook Health and Science Center, Toronto; David Wright, Queen's University; Hans J. Kreder, Sunnybrook Health and Science Center, Toronto; Cari Whyne, Sunnybrook Health and Science Center, Toronto

Purpose: The distribution of weight bearing area within the acetabulum is of importance in addressing trauma to the acetabulum, hip joint deformities and causes of osteoarthritis. According to Wolf's law, bone density can indicate loading patterns experienced. The objective of this study was to characterize distributions of acetabular bone density patterns by regions in the normal population. **Method:** CT scans of 22 subjects, mean age 70.6 with no evidence to hip joint pathologies were analysed. Bone density distribution maps were generated within AmiraDEV4.1 image analysis software using custom written plugins (Visage Imaging, Carlsbad, USA). Acetabular cup surfaces were semi-automatically segmented from the reconstructed CT volumes with an atlas-based approach. The acetabular cups were expanded 2.5 mm into the acetabular bone, and surface bone densities were calculated as the average bone density within ±2.5mm. The distribution maps were analysed using zones to spatially classify areas of high and low bone density in a healthy population. The acetabular cups were aligned using the acetabular rim plane that was landmarked, and by rotating the cups, such that a 900 abduction angle and a 00 anteversion angle were achieved. The grid used was divided to quadrants, and subdivided into radial thirds of the average rim radius. The correspondence of left and right density maps was investigated by comparing the average bone density in corresponding zones and across the population. **Results:** High bone densities were found around the roof of the acetabulum aligning with the femoral mechanical axis during standing. The highest average bone density were found to be the superior and posterior walls of the acetabulum, corresponding to regions 8, 9, and 12 compared to other regions of the acetabuli ($P<0.01$). A strong correlation was found between left and right sides within subjects ($R=0.91$, $P<0.05$); and weaker correlation was also found for overall average bone density, ($R=0.77$, $P<0.05$). **Conclusion:** The location of the zones with the highest average

bone density agrees with cadaveral studies of the maximum contact stress in the acetabulum (zones 9 and 12). [1,2]. It may explain why trauma to these areas carries a higher risk for early arthritic changes.