A Novel Method for Prevention of Intraoperative Fracture in Cementless Hip Arthroplasty: Vibration Analysis During Femoral Component Insertion

R. Michael Meneghini1,2, Philip Cornwell2, Nathaneal Yoder3, Andrew Crisman4, Molly McCuskey4, Aaron G. Rosenberg3
1Joint Replacement Surgeons of Indiana Research Foundation, Indianapolis, IN; 2Department of Mechanical Engineering, Rose-Hulman Institute of Technology, Terre Haute, IN; 3Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, IL; 4Los Alamos National Laboratory, Los Alamos, NM
rm_meneghini@yahoo.com

Introduction: Recently, MIS surgical techniques in total hip arthroplasty have been reported to offer advantages over standard surgical approaches. However, smaller incisions may diminish the ability to adequately visualize the proximal femur and potentially increase the risk of intraoperative femur fractures. This potential decrease in visual ability places additional emphasis on the surgeon’s auditory and tactile senses in determining the optimal interference fit of the implant within the geometry of the proximal femur, required for maximal implant stability. Intraoperative periprosthetic femur fracture may occur if the implant is impacted past the point of optimal interference fit, subjecting the cortical bone of the proximal femur to excessive hoop stresses. Intraoperative fractures, especially if unrecognized, decrease the mechanical stability of the component and increase the risk of implant failure.

The objective of this study was to determine if damage identification techniques, such as monitoring vibration characteristics of the impaction process, can supplement the surgeon’s tactile and auditory senses to accurately determine maximal femoral component interference fit and stability. The study hypothesis was that vibration characteristics and metrics generated during the impaction process will provide information that will assist the surgeon intraoperatively in determining when maximal interference fit and seating of the femoral implant is reached prior to detrimental periprosthetic fracture.

Materials and Methods: A tapered cementless femoral component was instrumented with accelerometers and a PZT patch [IMAGE1] and data was obtained as the femoral component was being impacted. The femoral components were impacted into five third-generation mechanical testing Sawbones specimens, as well as into eight fresh-frozen cadavers. The mechanical testing replicate femurs and fresh-frozen cadaveric femurs were prepared by an orthopedic surgeon using standard implant–specific instrumentation and the femoral component was impacted until specimen fracture or final seating if fracture was unable to be produced. Acceleration measurements were taken in the direction of impaction and in the two transverse directions. An instrumented hammer with an integrated forced transducer was used to measure the force input. Signal processing techniques were applied to the acceleration time histories [IMAGE2] to determine if features exist that can be used to determine when the implant is fully seated. The PZT patch was used as an actuator, as well as a sensor, and impedance measurements were obtained. All data was acquired using an eight channel dynamic signal analyzer and data acquisition software.

Results: Metrics were analyzed from PZT excitation data during insertion into the mechanical testing specimens. The two most correlative indices were the frequency of the anti-resonance in the 10.5 to 12 kHz band and the peak magnitude in the 9 to 11 kHz band. Both demonstrate good convergence as the prosthesis was inserted. Impact test data from the mechanical testing specimens revealed the sum of the acceleration data divided by the sum of the impact force was a metric that also demonstrates reliable convergence with implant insertion. This pattern of convergence indicates these two indices likely demonstrate the ability to accurately predict optimal implant seating.

The time to 99% total norm metric using the z-direction acceleration data was the most reliable metric of the cadaveric data analysis. The metric controls for the variability of each specimen and variability of each input force by focusing solely on relative changes in the z-direction acceleration signal. Interestingly, this metric was not successful when used on the replicate femur data. This time to 99% total norm metric demonstrates a decreasing trend that corresponds to the seating of the prosthesis into the specimen for most cadaver femurs.

Discussion: This methodology is promising and has the potential to enable intra-operative determination of maximal femoral implant seating and provide the surgeon valuable information to potentially prevent intra-operative fractures. In particular, the percent norm signal processing technique utilized in the cadaveric data proved to be a successful method for determining the optimal femoral com-