Radiographic Validation of a Non-invasive Method of Measuring Hip Joint Reaction Force Using a Cartilage Relaxation Technique

Joseph Schaffer MD1, Daniel Vasconcellos2, Nathan Kaplan MD1, Noorullah Maqsoodi BS2, Mark Olles PhD2, John Elfar MD1, Brian Giordano MD1

1Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, Rochester, NY 14642
2Department of Manufacturing & Mechanical Engineering Technology, Rochester Institute of Technology, 78 Lomb Memorial Drive, Rochester, NY 14623

Introduction

Joint reaction forces (JRF) and contact pressures are classically measured using destructive techniques which require dissection and interposition of materials into the joint, fundamentally altering the normal joint mechanics.1-3 Without an alternate method available, modern hip JRF biomechanical studies involve this stripping of perarticular tissues, potentially sacrificing accurate measurements.4,5 As hip arthroscopy is increasingly employed for minimally invasive treatment of hip pathology, there may be a need for minimally invasive biomechanical measurement techniques that reflect joint contact forces more accurately, yet virtually all hip biomechanical studies in this field strip the joint of its perarticular tissues.7-12 This study’s objectives were to demonstrate that a non-invasive, non-destructive technique for measuring JRF was feasible in the hip and to validate this concept using simultaneous radiographic imaging.

Background

A novel method of measuring forces within joints, originally developed in an animal model13, has been refined and applied to human cadaver models14,15. In resting conditions, articular cartilage is subjected to miniscule compressive deformation by the sum of tension forces in the soft tissues surrounding the joint. By continuously and very slowly distracting a joint, while simultaneously measuring distraction force and displacement in a highly sensitive materials testing system, the point at which the cartilage is fully relaxed can be observed as an inflection point in the force-distraction curve. At this point, the distraction force applied is equal and opposite to the original compressive load experienced by the cartilage and therefore represents the true resting JRF.

Methods

Twenty fresh frozen male human cadaver hemipelves were instrumented with a custom-made retrograde nail-plate construct in the femur and an iliac-crest locking plate. These otherwise fully-intact specimens were rigidly mounted for tensile testing (Instron Model 1122). With the hip in the neutral position, the joint was distracted 5mm along the axis of the femoral shaft at a rate of 0.4mm/s, while simultaneously measuring the force required for distraction. Force-displacement curves that were generated allowed the best-fit polygonal model to be calculated with resulting revelation of the native state JRF. Next, the joint capsule was vented under fluoroscopic control using an 18 gauge spinal needle and distraction was repeated with fluoroscopic images captured at 0.5mm increments. All testing was repeated at least three times, and two specimens were excluded for severe osteoarthritides (<2mm joint-space).

Figure 1: Depiction of Experimental Apparatus. The schematic drawing depicts the fully instrumented hemipelves specimen mounted within the tensile tester. The otherwise fully intact specimen (B) was fixed rigidly with custom hardware: at the iliac crest with a custom modified locking plate and screws (A), and at the femur with a custom modified retrograde nail with percutaneous interlocking screws (C). This allowed longitudinal distraction through the joint. A Carlm X-ray machine was positioned around the tensile tester to allow simultaneous acquisition of fluoroscopic imaging.

Figure 2: Illustration of Force vs. Distraction curve. Curves demonstrated an initially steep but decreasing (concave-down) slope, followed by an inflection point, a linear region and then a relatively non-linear increasing (concave-up) slope with further distraction (Point C). Illustrations and air arthograms are represented for reference Points A, B, and C. Air arthograms demonstrate a visible air crescent between the cartilage surfaces, appearing at the inflection point (B), and widening with further distraction (C).

Results

Statistical analysis was performed. Normality testing demonstrated the samples were collected from normally distributed populations (n=18 for both). High reproducibility between repeated measurements was found within specimens (i.e. standard deviation was less than 0.5% of measured values). The variability between individual specimens was significantly higher.

Force-displacement curves demonstrated an initially steep but decreasing (concave-down) slope, followed by an inflection point, a linear region and then a relatively non-linear increasing (concave-up) slope with further distraction. Under fluoroscopy, air arthograms confirmed that cartilage relaxation and surface separation consistently occurred at the measured force-distraction inflection point. (Figure 2)

The mean JRF for Native State was 110.5 ± 54.3 N and the mean JRF after Air Arthrogram was 100.2 ± 45.2 N. In other words, capsular venting decreased resting JRF by 10.3 N. Paired T-test comparison (α = 0.05) demonstrated that this difference was significant (p = 0.026).

Conclusions

This study describes and validates a reproducible method of measuring hip JRF that preserves all periarthrotic stabilizing soft tissue structures. To our knowledge, this is the first study in any joint to correlate force-displacement data with fluoroscopic images, confirming the method’s central premise: That JRF is equal to the measured force-distraction inflection point. This may be ideally suited for application in biomechanical studies of minimally invasive arthroscopic hip surgery.

References