A Computational Modeling Approach to Optimize Cup Coverage and Minimize Impingement Risk using Subject-specific Activities of Daily Living

Josh R Baxter, PhD[1]
Jenna Bernstein, MD[1]
Neza Stefanic[1]
Michael W Hast, PhD[1]

[1]Department of Orthopaedic Surgery
University of Pennsylvania

Introduction

Total hip arthroplasty (THA) is a highly effective surgery for treating end-stage hip osteoarthritis. However, impingement between the femoral and acetabular components has been linked to poor outcomes, dislocations, and implant failures. Classic work by Lewinnek et al.[1]identified an acetabular cup 'safe zone' as a critical factor for reducing dislocation risk, which has been challenged by recent clinical studies leveraging larger cohorts.[2,3] Activities of daily living associated with THA dislocation vary amongst individuals,[4,5] highlight the need for implant positioning recommendations based on patient-specific motions.

The objective of this study was to establish a simulation framework for optimizing THA acetabular cup positioning based on patient-specific biomechanics. Development of this simulation tool using an open-source musculoskeletal modeling platform for determining implant geometry and surgical placement based on patient-specific motions, provides potential for future technique implementation in the orthopaedic community.

Methods

A healthy-young male (22 years, BMI 20.8) performed activities of daily living that are considered to increase the risk of implant dislocation in total hip arthroplasty patients.[4] Sit to stand motions from low and normal-height chairs, shoe tying, bending at the waist to pick up an object from the floor, and pivoting at the waist, performed ten times each, were measured using a 12-camera motion capture system (Raptor Series, Motion Analysis Corp, Santa Rosa, CA), while ground reaction forces were acquired from three embedded force plates (BP600900, AMTI, Watertown, MA). Written-informed consent was provided in this IRB approved study.

Component impingement and cup coverage were calculated using a musculoskeletal modeling paradigm (Figure 1A).[6] The musculoskeletal model was initially scaled to fit anatomical landmarks of the healthy-young male. Model motions were subsequently calculated to match the experimentally-collected motion data, using an inverse kinematics paradigm. In order

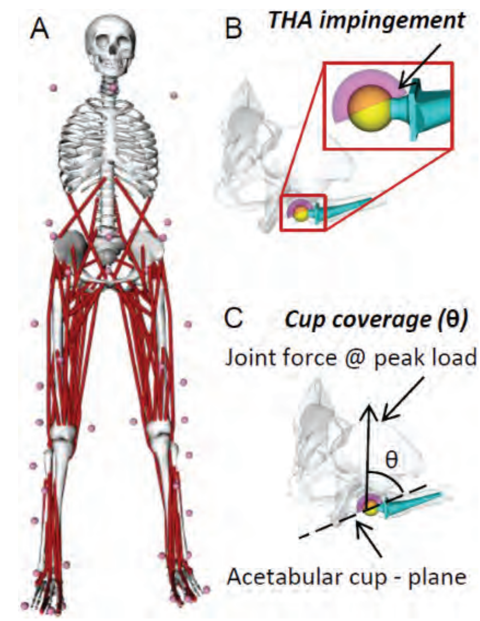

Figure 1. **(A)** Subject-specific anatomy was used to scale a musculoskeletal model that was used to calculate **(B)** THA impingement and **(C)** cup coverage during the high-risk activities performed in this study.

to calculate the joint reaction force magnitude and direction at the hip joint for determination of cup coverage angle, static optimization was performed next. Lastly, an elastic foundation model detected contact between the acetabular cup and femoral neck, providing instances of collision between the two THA components.[7]

The effects of cup positioning on cup coverage and component impingement were tested by simulating all combinations of inclination [20 – 60°] and version [0 – 40°] values in two-degree increments, resulting in a total of 441 possible cup positions. The angle between the joint reaction force and the plane of the cup at peak joint loading (Figure 1B) defined cup coverage for each simulation. Hip impingement was defined to occur in any simulation in which the contact forces between the acetabular cup and femoral components were non-zero (Figure 1C). These analyses were repeated for all ten trials of each of the five high-risk motions. Heat maps were generated for each activity to provide visualization of 1) the cup coverage angle at peak joint load and 2) the odds of movement completion without impingement. The resultant heat maps were further combined to demonstrate optimal cup positioning based on the observed patient-specific motions.

Results

Component impingement and cup coverage proved sensitive to both cup position and movement type. Activities requiring a large degree of hip flexion are prone to reduced cup coverage and impingement when cup version angles are reduced and inclination is increased (Figure 2). This relationship is more pronounced in component impingement than cup coverage. Pivoting at the waist, which causes external rotation of the THA, produces the opposite effect on cup coverage and component impingement with respects to cup positioning: increased version and decreased inclination appear to be risk factors for suboptimal biomechanics.

Lowest risk of impingement was observed when the cup positioning was between 10 to 30 degrees version and 20 to 40 degrees inclination. Cup coverage was greater than 30 degrees in a small linear-range of cup positions, from 10 degrees version and 20 degrees to 30 degrees and 60 degrees inclination. These two factors were used to establish the patient-specific 'safe zone' that mitigated the risk of poor cup coverage and impingement (Figure 3)

Discussion

A computational modeling framework was developed to identify patient-specific 'safe zone' that is sensitive to both cup positioning and patient-specific motions (Figures 2 and 3). Current efforts are focused on optimizing implant positioning to minimize the amount of loading near the rim of the acetabular cup, which affects both wear and dislocation rates.[8] Motion data from a healthy-young control confirmed that THA cup coverage and component impingement detected using this framework were sensitive to both cup positioning and subject biomechanics. While this specific data set does not have immediate clinical relevance, it has demonstrated a viable simulation framework for surgeons, that could be leveraged to optimize THA cup coverage and minimize impingement in patient populations.

Clinical studies have debated the 'safe zone' for patients with total hip arthroplasty.[1–3] In a series of 300 total hip replacements, nine (3 per cent In addition to studying the implications of cup positioning and patient-specific motions

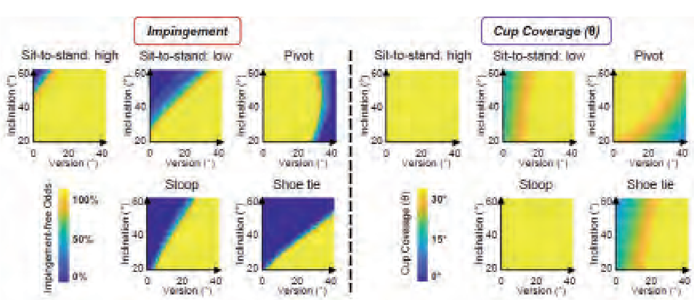

Figure 2. Component impingement cup coverage were established for each 'high-risk' activity throughout a range of cup positions and visualized in heat maps. Cup positions that did not impingement and maintained at least 30 degrees of cup coverage were yellow, while cup positions with impingement events and poor cup coverage were blue.

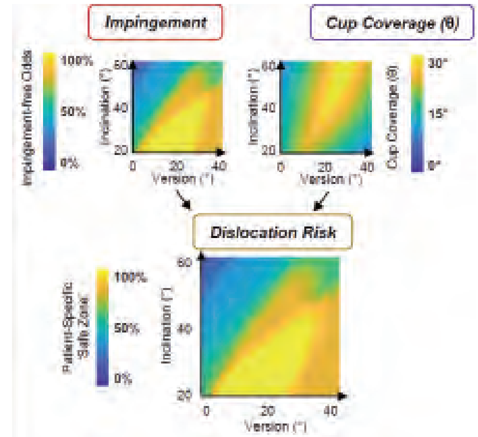

Figure 3. Component impingement and cup coverage heat maps were combined to establish an overall dislocation risk. Cup positions that avoided impingement events and maintained at least 15 degrees of cup coverage were considered to be the patient-specific 'safe zone'.

on cup coverage and impingement, this modeling framework can test a myriad of other factors; varying implant geometry, femoral anatomy and positioning, pelvic bony geometry, and lumbosacral spinal deformities among many others. Linking these surgical and patient factors with cup coverage and impingement may highlight numerous mechanisms of dislocation and implant wear.

Conclusions

Our results that cup coverage and impingement are unlikely to be the drivers of THA dislocations in commonly implanted cup positions—for example, 15 degrees version and 30 degrees inclination—suggest that other patient and surgical factors, such as altered movement patterns or soft-tissue constraints, may be important to consider when discussing total hip arthroplasty.

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