The Influence of Squat Kinematics and Cam Morphology on Acetabular Stress

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Purpose: To evaluate the effect of varying degrees of simulated cam morphology on acetabular stress magnitude and location using a finite element model with 1 subject that incorporates population-specific hip/pelvis kinematics during a squat task. **Methods:** A reference model of the hip joint was created from magnetic resonance images obtained from 1 asymptomatic 28-year-old man without femoroacetabular impingement (FAI) morphology or hip dysplasia (alpha angle 41.9°, lateral center edge angle 34.0°, neck-shaft angle 137°, and no visible articular cartilage lesions or bone marrow edema on magnetic resonance). The femoral head/neck geometry was manipulated to mimic different cam morphology severities as reported in a previous study (minimum, moderate, and large). Peak hip and pelvis squat kinematics from healthy individuals (hip flexion 112.6°, abduction 10.5°, internal rotation 14.8°) and persons with FAI (hip flexion 106.3°, abduction 10.5°, internal rotation 8.9°) were applied to the control and cam models. Relative acetabular joint stress values and location of contact were the variables of interest. **Results:** Average von Mises stress values for control, minimum, moderate, and large cam models were 9.64, 9.27, 11.36, and 28.43 MPa, respectively. Contact in the control and minimum cam models occurred within the acetabular cup. In the moderate and large cam models, contact shifted anterosuperiorly within the acetabular cup and to anterosuperior acetabular rim, respectively. **Conclusions:** Despite simulating lower degrees of hip flexion and internal rotation, increased stress and a shift in contact location were observed in the simulated models of FAI. This finding suggests that decreased hip internal rotation in this population during functional tasks may be the result of bony abutment. **Clinical Relevance:** Clinicians should be cautious about prescribing deep squats for persons with cam morphology. Performing squat exercises with neutral or external hip rotation may limit bony abutment at high hip flexion angles.

The term femoroacetabular impingement (FAI) refers to hip pain and pathology in the presence of specific bony morphology. Cam FAI morphology is defined by an increase in bone at the femoral head-neck junction.[1,2] The less spherical, cam-type femoral head has been reported to cause a shift in contact location from the acetabular cup and femoral head to the anterosuperior acetabular rim and the femoral head-neck junction.[3,4] Impingement occurs with actions that involve large degrees of hip flexion and hip internal rotation.[5-8] Therefore, knowledge of the interplay between both bony morphology and joint kinematics in persons with cam FAI is important to understanding the cause of this condition.

In a previous study,[9] it was reported that persons with cam FAI exhibited decreased pelvis posterior tilt and decreased peak hip internal rotation compared with persons without FAI during a deep squat task. Decreased posterior tilt of the pelvis would contribute to impingement due to increased approximation between the acetabulum and the femoral head. Decreased hip internal rotation may be the result of a behavioral modification to avoid the pain of mechanical impingement or hip internal rotation may be diminished as a result of bony abutment. Causes of reduced hip internal rotation in persons with FAI have not been determined. Furthermore, it is not known how much of a cam lesion would be necessary for the contact location to shift or for contact stress to increase given these altered hip and pelvis kinematics in persons with FAI.

Although previous finite element analyses and computational models have examined the influence of

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FAI on joint contact mechanics,[7,10-13] only 1 study has directly incorporated kinematics from persons with cam FAI and control subjects. Ng et al.[14] used finite element modeling to simulate a maximum depth squat task using the bony morphology of 2 persons with cam FAI and 2 persons without cam FAI to determine the forces across the acetabular cartilage and underlying bone. Although the bony morphology differed between the models, it was not clear if the kinematics were different between these participants. In addition, the participants with FAI in the study by Ng et al. had extreme cam morphology. To date, stress profiles in the presence of small-to-moderate cam morphology have not been explored using kinematic profiles of persons with cam FAI.

Given the potential contribution of hip and pelvis kinematics to FAI, the purpose of the current study was to evaluate the effect of varying degrees of simulated cam morphology on acetabular stress magnitude and location using a finite element model with 1 subject that incorporates population-specific hip/pelvis kinematics during a squat task. We hypothesized that there would be differences in acetabular joint stress magnitude and contact location among the models.

Methods

Subject

One male participant (university student) was recruited for this study through the use of flyers over a 1-year period. Exclusion criteria included lower extremity or low back pain in the past 6 months, a history of hip pain or hip surgery, an alpha angle of ≥50.5°, or a lateral center edge angle of ≥38°. A clinical examination was performed to rule out hip symptoms. Specifically, subjects were excluded if they had a positive log roll test,[15] greater than 5 cm asymmetry between sides with the Flexion ABduction External Rotation test,[16,17] or pain with internal rotation of the hip in 90° of hip flexion.[18] Before participation, the subject was informed of the purpose of the study and provided written institutional review board approved informed consent and Health Insurance Portability and Accountability Act authorization.

Magnetic Resonance Assessment

Magnetic resonance (MR) images of the hip and pelvis were obtained with the participant supine in neutral hip alignment (toes pointed toward ceiling) using a sagittal three-dimensional high-resolution, fat-suppressed, fast spoiled gradient recall echo sequence with the repetition time of 16.3 ms, echo time of 2.1 ms, flip angle of 12°, matrix 256 × 256, 1 mm slice thickness, and a 10-cm field of view in a 3 Tesla MR scanner (General Electric Healthcare, Milwaukee, WI).

Finite Element Model Development

MR images of the femur and hemipelvis were manually segmented using a commercial software package (Sliceomatic, Tomovision, Montreal, Quebec, Canada), and the femur and hemipelvis meshes were created using a finite element preprocessor (Hypermesh, Altair Engineering, Troy, MI). The femur was modeled as a rigid body and the acetabulum was modeled using homogeneous, isotropic, tetrahedral continuum elements with an elastic modulus of 17.0 MPa and a Poisson ratio of 0.30.[19,20] Three different cam models were created by manually adding nodes to the control model femur at the 1:30 position of the femoral head-neck junction to manipulate the alpha angle. Although there are a variety of anatomical factors that may influence contact mechanics at the hip, the alpha angle has been consistently linked to pathology.[21-24] The 1:30 location was chosen as a less spherical femoral head in this area has been most associated with the development of hip pain.[25] The femoral head-neck junction morphology was recreated 3 separate times to correspond to: (1) the minimum cam bony morphology required to establish the presence of cam FAI as defined in a previous study[9] (alpha angle 50.5° in the oblique axial plane[26,27]) (referred to as “minimum”), (2) the average cam bony morphology for persons with cam FAI from a previous deep squat kinematic study (alpha angle 54°) (referred to as “moderate”), and (3) the maximum cam bony morphology for persons with cam FAI in this previous study (alpha angle 66°) (referred to as “large”).[9]

After the femoral head-neck geometry was altered, the respective meshes were recreated using an element size of 1 mm. Using the deep squat kinematic data from a previous study,[9] the mean three-dimensional hip angles at the time of peak hip flexion for the control group were used in the control model and the mean three-dimensional hip angles for the cam group were used in all of the cam models (Table 1). Briefly, the participant was positioned with the feet parallel and pointed straight forward during the squat task to correspond to the neutral rotation position of the participant in the magnetic resonance imaging (MRI) scanner.[4] The pelvis and femur segments were rotated about the center of the femoral head to recreate these hip joint angles. Detailed procedures used to obtain kinematic data from a deep squat task in persons with and without cam FAI have been reported elsewhere.[4]

Finite element analysis was performed using a nonlinear solver (Abaqus, SIMULIA, Providence, RI) using a hard contact algorithm with the femur as the master surface and the acetabulum as the slave surface, with a surface-to-surface, small sliding contact and a surface coefficient of friction of 0.02.[28] The acetabulum was constrained in space and the 3 rotational degrees of freedom of the femur were constrained, although

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