Hip Joint Reaction Force Contributions to Acetabular Edge Loading in Dysplastic Hips: A Subject-Specific Musculoskeletal Modeling Study

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INTRODUCTION: Developmental dysplasia of the hip (DDH) is a known risk factor for acetabular labral tears, particularly in the antero-superior region, which may be attributed to abnormal loading near the acetabular edge.[1,2] Two determinants of acetabular edge loading are the hip joint reaction force (HJRF), including its magnitude and direction, and the hip bony geometry. Finite element and discrete element contact models have demonstrated how dysplastic hip geometry affects intra-articular contact stresses,[2,3] but typically used loading conditions from total hip arthroplasty databases or DDH group averages rather than subject-specific HJRFs. The limited number of musculoskeletal modeling studies on DDH have reported HJRF traits unique in dysplasic hips,[4,5] but whether such DDH-specific HJRFs contribute to altered acetabular edge loading remains unknown. Our objective was to compare acetabular edge loading during gait between DDH and healthy hips by quantifying subject-specific HJRFs and their projections onto the acetabulum. We hypothesized that due to poor antero-superior acetabular coverage, angles from HJRF to the anterior and superior edges would be smaller in DDH hips, and the magnitude of forces projected from HJRF to these directions would be higher.

METHODS: 9 Healthy (6F, 26±4 y/o, BMI: 23.8±4.5 kg/m²) and 9 DDH subjects (6F, 26±7 y/o, BMI: 22.7±3.1 kg/m²) were enrolled after IRB approval and informed consent.[2,3] Normal hip morphology of the Healthy subjects and pelvic bony deformities in the DDH subjects were both confirmed by a radiologist. Barefoot, self-selected speed gait data were collected in a motion capture laboratory.[2] Computed tomography scans of the pelvis and proximal femur bony geometry were reconstructed in 3D, imported to a musculoskeletal model (OpenSim) with 96 muscles, and used as the reference to update the model’s muscle paths. Subject-specific hip joint centers (HJCs) in each model were moved to the centroid of a sphere fit to the femoral head, assumed fixed in the acetabulum (i.e. rotation-only hip joint). Subject-specific HJRFs, defined as force vectors originating from the HJC, were computed over a gait cycle using model-estimated muscle forces via static optimization.[5] An acetabular edge line (AEL) was created from virtual landmarks placed along the rim (Fig. 1). The acetabular rim was divided in three regions represented by respective landmarks on the AEL (antero-lateral (AL), immediately distal to the anterior inferior iliac spine; supero-lateral (SL), the most superior point of AEL; and postero-lateral (PL), the most posterior point of AEL). Three spatial vectors from HJC to the AL, SL, PL points represented the directions along which hip loads were exerted from the femoral head to the acetabular edge. Angles between HJRF and the AL, SL, PL edges were calculated to quantify the proximity of the HJRFs to the edge. Projected forces of HJRF along these directions were also computed (Fig. 1). Next, a plane was fit to the AEL to estimate the acetabular border (acetabular edge plane, AEP), and its medially-directed normal (AEPn) was defined as the direction of hip joint compression (Fig. 1). Angles and projected forces from HJRF to AEPn were then computed. Lastly, the distance from HJC to AEP was calculated to represent the position of the femoral head relative to the acetabulum. HJC-to-AEP distances, resultant HJRFs, angles and projected forces from HJRF to AEPn, AL, SL, PL directions were compared between DDH and Healthy at the times of two HRF peaks, first during weight acceptance (‘JRF1’) and then in late stance transition to push-off (‘JRF2’), using two-tailed independent-samples t tests (α=0.05).

RESULTS: DDH subjects had larger HJC-to-AEP distances compared to Healthy [-9.8±4.1 vs -4.7±2.4 mm, p=0.005]. Resultant HJRFs were higher at JRF2 in DDH [5.6±1.4 vs 4.7±0.9 xBody Weight] but not statistically different. For DDH, angles from HJRF to AEPn (Fig. 2A) were significantly larger at both JRF1 [52.4±4.2° vs 45.2±4.9°, p=0.004] and JRF2 [59.4±4.9° vs 54.9±4.1°, p=0.049]; however, the magnitudes of projected forces from HJRF to AEPn were not different at either time (Fig. 2B). Also for DDH, angles from HJRF to AL (Fig. 2C) were smaller at JRF1 [53.5±8.8° vs 63.0±8.3°, p=0.032], but not at JRF2. As a result, projected forces from HJRF to AL (Fig. 2D) were higher only at JRF1 [1.9±0.6 vs 1.4±0.3 xBW, p=0.030]. Lastly, angles from HJRF to SL (Fig. 2E) were smaller at both JRF1 [24.0±7.8° vs 39.2±5.0°, p<0.001] and JRF2 [28.2±6.9° vs 39.0±9.0°, p=0.004], but projected forces from HJRF to SL (Fig. 2F) were only higher at JRF2 [4.8±1.1 vs 3.6±0.7 xBW, p=0.012]. Angles and projected forces from HJRF to PL were not different between groups.

DISCUSSION: As hypothesized, compared to Healthy hips, HJRFs in DDH were directed closer to the AL and SL edges of the acetabulum. Consequently, projected forces from HJRF to these regions were also higher for DDH, although the inter-group differences depended on the phase of gait (i.e. JRF1 vs JRF2). These differences could be attributed to poorer femoral coverage in DDH, indicated by larger distances from HJC to AEP, which may have altered muscle paths and resultant hip loads. Furthermore, the DDH acetabula were shallow and had high angles of inclination, which shifted the direction of joint compression (i.e. AEPn) to be less superior, hence may require higher resultant HJRFs to compress and stabilize the hip.[5] Shallow anterior and superior borders of the DDH acetabula mean the edge may be closer to the HJRF direction, which could increase edge loading in gait phases with high HJRF magnitudes (e.g. during late stance in the SL direction). However, a higher HJRF magnitude does not always elevate the edge loads. For example, HJRFs in DDH hips were directed closer to the AL edge at JRF1 but not at JRF2, and correspondingly, projected AL edge forces were significantly higher than Healthy only during weight acceptance. Although local stress patterns along the acetabular rim may not be described without labral tissue geometry and mechanical properties, the angles and projected forces from model-estimated, subject-specific HJRFs could help inform edge loading risks by incorporating the collective effects of movement pattern, muscle paths, and acetabular bony morphology.

SIGNIFICANCE: Acetabular labral tears are prevalent in DDH and contribute to joint degeneration. Analyzing subject-specific HJRFs in context with detailed acetabular geometry may help clarify the morphological and mechanical risk factors for labral tears in DDH hips. Our findings support the concept of higher acetabular edge loads in dysplastic hips, and provide new subject-specific analyses of HJRFs that can inform clinical interventions to influence joint load patterns, such as hip preservation surgery and movement retraining.


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Figure 1: Diagram of the AEL (purple line), AEP (gold plane), and HJRF projected in AEPn, AL, SL, PL directions on the acetabular geometry. HJRF shown in diagram depicts the resultant hip load during late stance and is directed anteriorly, away from PL direction.

Figure 2: Angles (top) and projected forces (bottom) from HJRF to AEPn (left), AL (middle), and SL (right) directions on the acetabulum during a gait cycle. Times of weight acceptance (JRF1) and transition to push-off (JRF2) highlighted in yellow; * = statistical significance.