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Finite element predictions of cartilage contact mechanics in hips with retroverted acetabula

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SUMMARY

Background: A contributory factor to hip osteoarthritis (OA) is abnormal cartilage mechanics. Acetabular retroversion, a version deformity of the acetabulum, has been postulated to cause OA via decreased posterior contact area and increased posterior contact stress. Although cartilage mechanics cannot be measured directly *in vivo* to evaluate the causes of OA, they can be predicted using finite element (FE) modeling.
Objective: The objective of this study was to compare cartilage contact mechanics between hips with normal and retroverted acetabula using subject-specific FE modeling.
Methods: Twenty subjects were recruited and imaged: 10 with normal acetabula and 10 with retroverted acetabula. FE models were constructed using a validated protocol. Walking, stair ascent, stair descent and rising from a chair were simulated. Acetabular cartilage contact stress and contact area were compared between groups.
Results: Retroverted acetabula had superomedial cartilage contact patterns, while normal acetabula had widely distributed cartilage contact patterns. In the posterolateral acetabulum, average contact stress and contact area during walking and stair descent were 2.6–7.6 times larger in normal than retroverted acetabula ($P \leq 0.017$). Conversely, in the superomedial acetabulum, peak contact stress during walking was 1.2–1.6 times larger in retroverted than normal acetabula ($P \leq 0.044$). Further differences varied by region and activity.
Conclusions: This study demonstrated superomedial contact patterns in retroverted acetabula vs widely distributed contact patterns in normal acetabula. Smaller posterolateral contact stress in retroverted acetabula than in normal acetabula suggests that increased posterior contact stress alone may not be the link between retroversion and OA.

Introduction

Hip osteoarthritis (OA) occurs in approximately 9.5% of the male population and 11.2% of the female population[1]. OA is thought to be initiated by mechanical factors and advanced by a combination of mechanical and metabolic factors[2–4]. For example, elevated or prolonged cartilage stresses can cause permanently altered levels of aggrecan synthesis[3]. Also, impact trauma resulting in high contact stress can cause fissuring[5]. Thus, deleterious cartilage contact stresses are of interest as a potential mechanical initiator of OA at the cartilage level.

At the joint level, bony pathologies including acetabular retroversion have been linked to increased rates of hip OA[6–8]. Acetabular retroversion is defined as the acetabulum opening more posterolaterally than normal. This is recognized on anteroposterior radiographs by the presence of a crossover sign, which indicates a prominent anterior acetabular wall, a deficient posterior acetabular wall, or both [Fig. 1][9]. There is a higher incidence of acetabular

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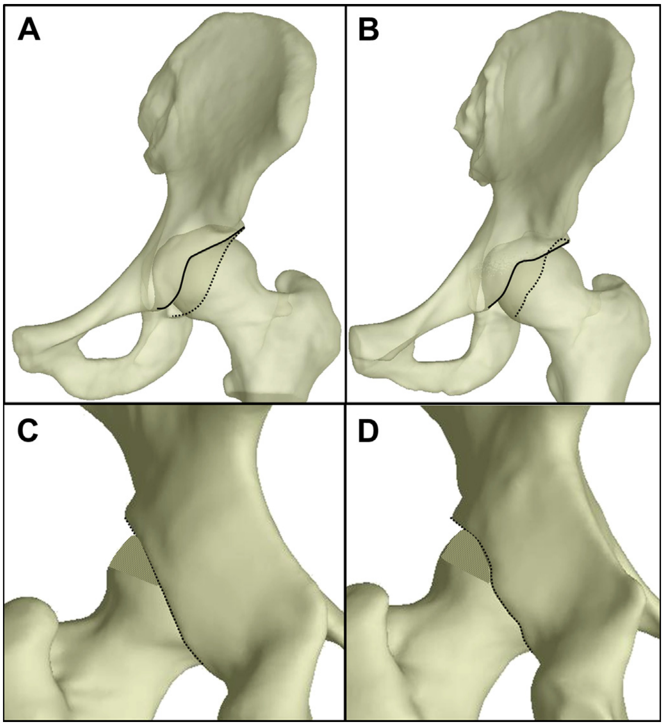

Fig. 1. Anterior views of hips with A – normal anatomy and B – acetabular retroversion. The anterior acetabular rim is outlined in solid back and the posterior acetabular wall is outlined in dashed black. While the posterior acetabular wall lies lateral to the anterior acetabulum over the whole joint in the normal hip, the posterior acetabular wall lies medial to the anterior acetabulum in the superior portion of the retroverted hip. As the lines progress distally, the anterior and posterior lines outlining the acetabulum cross each other, creating the crossover sign. Posterior views of hips with C – normal anatomy and D – acetabular retroversion. The relative undercoverage of the femoral head in the hip with acetabular retroversion near the superior portion of the hip is highlighted.

retroversion among osteoarthritic hips than among healthy hips[6,8,9]. Specifically, in a series of anteroposterior radiographs, only 6% of the subjects without OA had a crossover sign, while 20% of the subjects with OA had a crossover sign. The presence of the crossover sign resulted in a significantly greater likelihood of OA[6]. In another study, subjects with acetabular retroversion had significantly narrower mean joint space than those without retroversion[8].

While clinical data suggest a link between acetabular retroversion and OA, the nature of that link remains unclear due to complications in the diagnosis of acetabular retroversion and the lack of methodical evaluations of the mechanics of the retroverted acetabulum. There is controversy regarding the precise definition of acetabular retroversion. Diagnosis based on the crossover sign from clinical radiographs has been questioned because of the effect of pelvic inclination on the crossover sign[10,11]. In addition, it is unclear whether altered mechanics result from relative posterior undercoverage of the femoral head or from anterior femoroacetabular impingement. Evaluations of hip morphology have demonstrated decreased posterior coverage of the femoral head in hips with retroverted acetabula compared to normal hips[12,13]. This could cause OA from decreased contact area and the resulting increased contact stress on the posterior acetabulum[7,12–15]. Alternatively, an acetabulum with normal posterior coverage but increased anterior coverage may also present as the crossover sign. Increased anterior coverage has caused retroversion to be associated with the diagnosis of pincer-type femoroacetabular impingement[16,17]. In the case of impingement, OA may result from a combination of anterior labral damage caused by impingement and posterior cartilage damage caused by the countercoup lesion[18–20]. Because the pathomechanics of acetabular retroversion are not fully understood, comparison of the contact mechanics between hips with retroverted and normal acetabula may provide insight into the link between retroversion and OA. Specifically, regions of altered cartilage contact mechanics could indicate whether posterior undercoverage results in decreased posterior contact area and increased posterior contact stress in hips with retroverted acetabula compared to hips with normal acetabula.

Subject-specific finite element (FE) models can be used to predict cartilage contact mechanics that cannot be measured *in vivo*. Previous FE analysis has demonstrated the variability in cartilage contact mechanics in the normal population, as well as altered cartilage contact mechanics in hips with acetabular dysplasia and acetabular overcoverage[21–24]. FE predictions of cartilage contact mechanics in retroverted hips have not been made but could lend valuable insight into mechanisms which lead to OA in this patient population. Therefore, the objective of this study was to compare cartilage contact mechanics between hips with normal bony anatomy and hips with acetabular retroversion during activities of daily living using a validated approach to subject-specific FE modeling[25].

Methods

Twenty subjects were recruited. All subjects gave informed consent to participate in the study and were recruited following Institutional Review Board approval (University of Utah Institutional Review Board #10983; the procedures followed were also in accordance with the Helsinki Declaration). Ten healthy control subjects with normal center-edge angles and no history of hip pain were drawn from a previous study (five male, body mass index 23.0 ± 3.9 kg m^{-2}, age 26 ± 4 years)[22]. Ten patients with a radiographic crossover sign on standardized radiographs, pain and clinical exams consistent with acetabular retroversion, and who subsequently received treatment for symptomatic acetabular retroversion were analyzed for the current study (nine male, body mass index 24.1 ± 2.7 kg m^{-2}, age 24 ± 7 years). To quantify the morphology of the hips, standard radiographic measurements were made. The lateral center-edge angle measures the coverage of the femoral head by the acetabulum[26]. Sharp's angle measures the acetabular inclination of the entire acetabulum, while the acetabular index measures the inclination of the acetabular roof[27,28]. The alpha angle is a two-dimensional measure of femoral asphericity, and it was measured in the Dunn view with external rotation because it provides the best correlation with three-dimensional measurements of asphericity[29]. The bony and articular surfaces were fit to spheres in order to evaluate the ratio of the acetabular to femoral head diameters.

Subject-specific geometry was acquired using computed tomography (CT) arthrography [Supplementary Fig. S1 and Supplementary Data][22,23]. Approximately 15–25 mL of contrast agent was injected under fluoroscopic guidance. Contrast was a 2:1 mixture of Xylocaine to Isovue 300. Manual traction was applied following the arthrography injection. CT images were acquired under constant traction applied via a hare-traction splint[22]. The CT field of view was adjusted to capture both hips (range: 331–500 mm). All images were acquired with 1 mm slice intervals and a 512×512 acquisition matrix.

CT images were segmented semi-automatically. Initial segmentation was done by thresholding, followed by manual segmentation to delineate regions which were visible but could not be captured using automated methods. All image data were resampled to three times the original resolution in all planes to facilitate smooth 3D reconstructions[22]. Cortical bone, trabecular bone and cartilage were segmented for the hemipelvis and proximal femur.

Segmented surfaces were discretized and represented using constitutive models from the literature [Fig. 2]. Cortical bone was

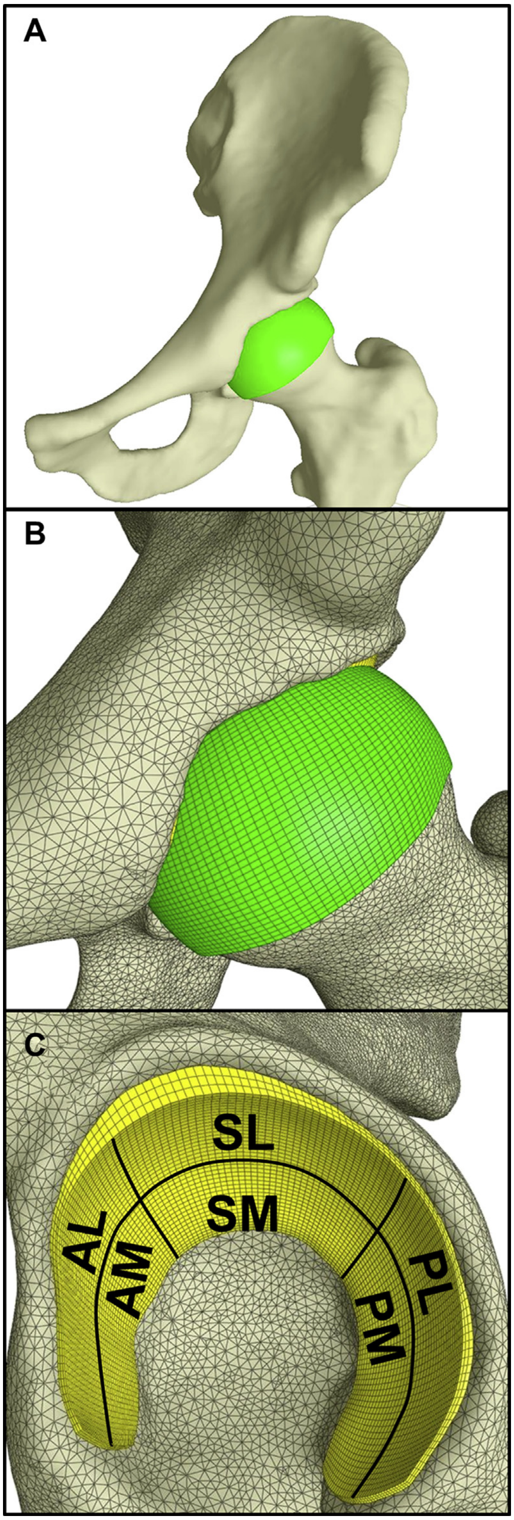

Fig. 2. Subject-specific FE models were generated from CT data. A – anteroposterior view of a subject-specific FE model showing the bones (white) and femoral cartilage (green). B – anteroposterior view of the joint space showing discretization of the bone into triangular shell elements and the femoral cartilage into hexahedral elements. C – lateral view showing discretization of the acetabular cartilage (yellow) into hexahedral elements and the six anatomical regions on the acetabulum used for analysis of the results (AL = anterolateral, AM = anteromedial, SL = superolateral, SM = superomedial, PL = posterolateral, PM = posteromedial).

discretized into triangular shell elements with position-dependent thickness[25]. Cartilage was discretized into hexahedral elements. Element densities were based on previous mesh convergence analyses[25]. Bone was represented as isotropic linear elastic ($E = 17$ GPa, $\nu = 0.29$)[30]. Cartilage was represented as neo-Hookean hyperelastic ($G = 13.6$ MPa, $K = 1359$ MPa)[25,31].

Boundary conditions from instrumented implant and gait data were applied to simulate average kinematics and kinetics[32]. Activities were chosen to cover a range of loads and anatomical positions. While kinematic joint angles were identical for all subjects, the applied load was scaled by subject body weight (BW). Five points through the stance phase of walking were simulated: heel strike (referred to as walking heel, 233% BW), between heel strike and mid-stance (referred to as walking heel-mid, 215% BW), mid-stance (referred to as walking mid, 203% BW), between mid-stance and toe-off (referred to as walking mid-toe, 204% BW) and toe-off (referred to as walking toe, 205% BW). Heel strike during descending stairs (referred to as descending stairs, 261% BW) and ascending stairs (referred to as ascending stairs, 252% BW) were also simulated. Maximum flexion during chair rise (referred to as chair rise, 135% BW) was simulated primarily due to the posteriorly directed load, which focused loading on the posterior acetabulum. All models were analyzed with NIKE3D[33] and post-processed using PostView[34].

Cartilage contact stress and contact area were evaluated on six anatomical regions of the acetabular cartilage surface: anterolateral, anteromedial, superolateral, superomedial, posterolateral and posteromedial [Fig. 2(C)][35]. Contact stress is the normal stress acting on the articular surface. Contact area was normalized to the total surface area in each region[22]. For each region and activity, statistical analysis between groups was completed using *t* tests when data were normally distributed or Mann–Whitney Rank Sum tests when data were not normally distributed. Normality was tested using the Shapiro–Wilk test. For each region and group, statistical analysis between activities was completed using paired *t* tests. Statistical analysis was completed in SigmaPlot (Version 11.0, Systat Software, Inc., San Jose, CA). Significance was set at $P \leq 0.05$.

Results

Morphological differences in addition to acetabular retroversion were present, with significant differences in the lateral center-edge angle and the alpha angle between the groups. The lateral center-edge angle, Sharp's angle and acetabular index were $33.5 \pm 5.4°$, $40.0 \pm 3.4°$ and $4.5 \pm 3.3°$ in normal hips and $27.8 \pm 5.5°$, $37.4 \pm 3.5°$ and $4.6 \pm 4.7°$ in retroverted hips, respectively ($P = 0.028$, 0.104 and 0.965, respectively). The alpha angle was $44.0 \pm 4.0°$ in normal hips and $61.7 \pm 13.0°$ in retroverted hips ($P < 0.001$). The ratios of the acetabular to femoral head diameters were 1.09 ± 0.02 and 1.07 ± 0.02 at the bony surfaces and 0.95 ± 0.02 and 0.96 ± 0.02 at the articular surfaces in the normal and retroverted hips, respectively ($P = 0.354$ and 0.455, respectively).

The location of contact in retroverted subjects tended to be focused more medially and superiorly than in normal subjects, while contact in normal subjects was more widely distributed [Fig. 3]. Contact patterns also shifted due to loading scenario, with a shift toward more posterior loading in both groups during chair rise [Fig. 4 and Supplementary Fig. S2]. However, trends of concentrated contact patterns in retroverted hips and widely distributed contact patterns in normal hips remained consistent across loading scenarios. Similar to previous findings, there was greater consistency between scenarios within each subject than between subjects within each scenario, indicating the importance of subject-specific geometry on contact pattern [Supplementary Fig. S2][22].

There were significant differences between the two groups in peak contact stress in the superomedial and posterolateral regions

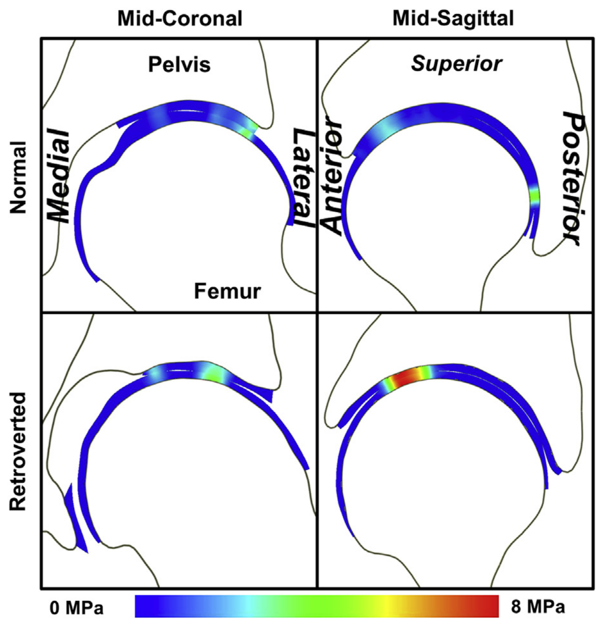

Fig. 3. Cross-sectional images of cartilage pressure during walking mid in the coronal (left column) and sagittal (right column) planes of representative normal and retroverted hips. The contact pattern was localized medially and superiorly in retroverted hips (bottom row), while normal hips had contact patterns that were more widely distributed over the articular surface (top row).

[Fig. 5(A) and Supplementary Fig. S3]. Peak contact stress in the posterolateral region was significantly larger in normal hips than in retroverted hips during walking heel-mid, walking mid, walking mid-toe, walking toe and descending stairs ($P = 0.022$, 0.006, 0.002, 0.002 and 0.042, respectively). Conversely, peak contact stress in the superomedial region was significantly larger in retroverted hips than normal hips during all walking scenarios ($P = 0.038$, 0.044, 0.003, 0.044 and 0.009 for walking heel, walking heel-mid, walking mid, walking mid-toe and walking toe, respectively). When the posterior acetabulum was loaded during chair rise, peak contact

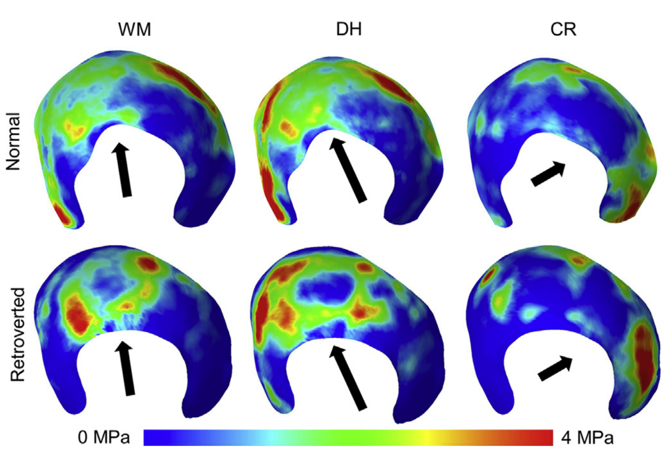

Fig. 4. Contact stress patterns averaged across all normal hips (top row) and across all retroverted hips (bottom row) during three activities. The arrows indicate the approximate direction and relative magnitude of the load during each activity. Both the direction of the applied load and the subject group influenced contact pattern. When the load was directed superiorly during walking mid, the contact patterns in both groups were primarily in the superior acetabulum. When the load was directed slightly anteriorly during descending stairs, the contact patterns were more anterior than during walking mid in both groups. When the load was directed posteriorly during chair rise, the contact patterns were primarily in the posterior acetabulum in both groups.

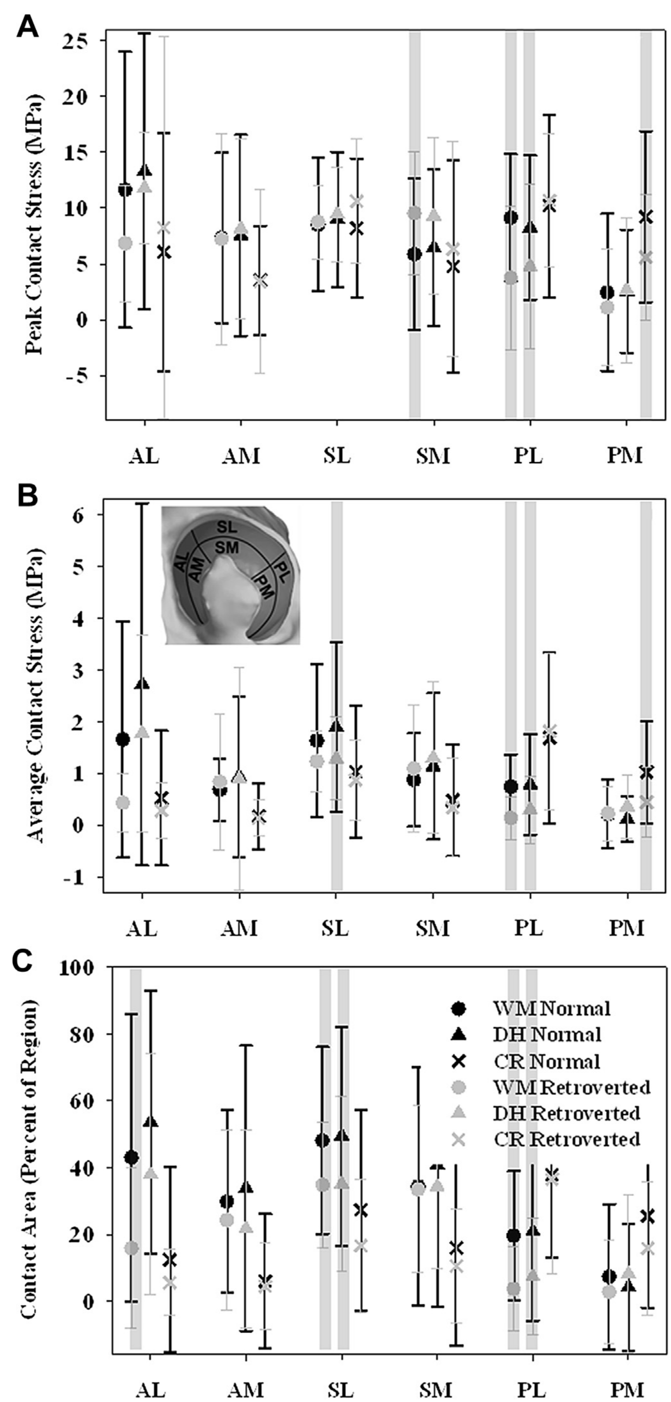

Fig. 5. Contact stress and area results for walking mid, descending stairs and chair rise loading scenarios in both groups ($n = 10$ in each group). Results are shown by anatomical region (AL = anterolateral, AM = anteromedial, SL = superolateral, SM = superomedial, PL = posterolateral, PM = posteromedial). A – peak contact stress. B – average contact stress. C – contact area. Peak contact stress in the superomedial region was larger in the retroverted hips than in the normal hips during walking mid. For all other significant differences, results were larger in the normal hips than in the retroverted hips. This included larger peak contact stress, average contact stress and contact area in the posterolateral region during walking mid and descending stairs, as well as larger peak and average contact stress in the posteromedial region during chair rise in the normal hips than in the retroverted hips. Gray highlights indicate $P \leq 0.05$. Error bars show 95% confidence intervals.

stress in the posteromedial region was significantly larger in normal hips than in retroverted hips ($P = 0.029$).

Average contact stress was significantly larger in normal hips than in retroverted hips in several activities in the lateral and posterior regions [Fig. 5(B) and Supplementary Fig. S4]. Specifically, average contact stress was significantly larger in normal hips than in retroverted hips in the posterolateral region during all walking activities and descending stairs ($P = 0.003$ for walking heel, $P \leq 0.001$ for all other walking activities, $P = 0.013$ for descending stairs). Average contact stress in the anterolateral region was significantly larger in normal hips than in retroverted hips in walking mid, walking mid-toe and walking toe ($P = 0.026$, 0.017 and 0.014, respectively). As with peak contact stress, average contact stress in the posteromedial region during chair rise was significantly larger in normal hips than in retroverted hips ($P = 0.006$). While average contact stress in the superomedial region tended to be larger in retroverted hips than in normal hips, the only significant difference was during walking heel ($P = 0.028$).

Contact area as a percentage of each region tended to be smaller in retroverted hips than in normal hips [Fig. 5(C) and Supplementary Fig. S5]. Percent contact area in the superolateral and posterolateral regions was significantly smaller in retroverted hips than in normal hips during all walking scenarios and descending stairs (in the superolateral region $P = 0.035$, 0.035, 0.025, 0.018, 0.021 and 0.048, respectively for walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe and descending stairs; in the posterolateral region $P = 0.005$, 0.007, 0.002, <0.001, <0.001 and 0.017, respectively). Percent contact area in the anterolateral region was significantly smaller in retroverted hips than in normal hips during walking heel-mid, walking mid, walking mid-toe, walking toe and ascending stairs ($P = 0.009$, 0.003, 0.003, 0.003 and 0.044, respectively). There were no significant differences in percent contact area in the medial regions.

Regional peak contact stress, average contact stress and contact area varied by loading scenario within each group. Many of the regional differences were between chair rise, which had a posteriorly directed load, and the other activities. Contact stress and contact area in the anterior and superior regions tended to be smaller during chair rise than during other activities, but contact stress and contact area in the posterior regions tended to be larger in chair rise than during other activities. In the normal hips, peak contact stress, average contact stress and contact area during chair rise were significantly smaller than during all other activities in the anterolateral region, but significantly larger than during all other activities in the posteromedial region (in the anterolateral region for peak contact stress $P = 0.006$, 0.012, 0.012, 0.004, 0.009, <0.001 and 0.001, for average contact stress $P = 0.005$, 0.003, 0.003, 0.003, 0.002, <0.001 and 0.002 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe, descending stairs and ascending stairs, respectively, for contact area $P = 0.002$ against walking heel and $P < 0.001$ against all other activities; in the posteromedial region for peak contact stress $P = 0.018$ against ascending stairs and $P < 0.001$ against all other activities, for average contact stress $P = 0.002$ against walking heel and $P \leq 0.001$ against all other activities, for contact area $P = 0.020$, 0.002, 0.006, 0.005, 0.005, 0.001 and 0.007 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe, descending stairs and ascending stairs, respectively). Average contact stress in the posterolateral region was significantly larger during both ascending stairs and chair rise than during all walking activities and descending stairs (for ascending stairs $P = 0.004$, 0.001, 0.002, 0.001, 0.001 and <0.001, for chair rise $P = 0.013$, 0.002, 0.001, 0.001, <0.001 and 0.002 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe and descending stairs, respectively). Average contact stress in the anteromedial region was significantly smaller during chair rise than during all walking activities and descending stairs ($P = 0.019$, 0.02, 0.01, 0.009, 0.01, and 0.021 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe and descending stairs, respectively). Contact area in the superolateral, anteromedial, and superomedial regions was significantly smaller during chair rise than during all other activities (in the superolateral region $P = 0.002$ against descending stairs and $P < 0.001$ against all other activities; in the anteromedial region $P = 0.006$, 0.006, 0.002, 0.001, 0.002, 0.004 and 0.031; in the superomedial region $P = 0.001$, 0.003, 0.011, 0.020, 0.025, 0.005 and 0.005 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe, descending stairs and ascending stairs, respectively). Contact area in the posterolateral region was significantly larger in chair rise than during all activities except walking heel and ascending stairs ($P = 0.003$ against walking heel, $P < 0.001$ against walking mid, walking mid-toe and walking toe, $P = 0.015$ against descending stairs). In the retroverted subjects, peak contact stress in the posterolateral region during chair rise was significantly larger than during all walking scenarios and descending stairs ($P = 0.012$ against walking heel, $P = 0.002$ against descending stairs and $P < 0.001$ against all others). Average contact stress was significantly smaller during chair rise in the anterolateral and superomedial regions than during all other activities and was larger during chair rise than during all other activities in the posterolateral region (in the anterolateral region $P = 0.036$, 0.012 0.004 0.003 0.001, <0.001 and 0.015; in the superomedial region $P = <0.001$, <0.001, 0.006, 0.013, 0.027, 0.006 and 0.002 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe, descending stairs and ascending stairs, respectively; in the posterolateral region $P < 0.001$ against all activities). Contact area during chair rise was significantly smaller than during all other activities in the anterolateral and superolateral regions (in the anterolateral region $P = 0.003$, 0.005, 0.004, 0.004, 0.002, <0.001 and 0.008; in the superolateral region $P = 0.002$, 0.002, 0.003, 0.002, 0.004, 0.004 and 0.002 against walking heel, walking heel-mid, walking mid, walking mid-toe, walking toe, descending stairs and ascending stairs, respectively). Contact area during chair rise was significantly larger than during all other activities in the posterolateral region ($P = 0.002$ against ascending stairs, $P < 0.001$ against all other activities).

Discussion

Unique contact patterns in the two groups affected the predicted contact stress and contact area. In many regions, both contact stress and percent contact area were lower in the retroverted hips than in the normal hips. Since force can be interpreted as stress integrated over a contact area, these results may seem counterintuitive. However, if the location of contact area and direction of the applied load are considered, the results are clearer. Contact area has an associated direction, normal to the articular surface at each point. In the retroverted hips, contact tended to be in the superior and medial regions of the acetabulum during walking, ascending stairs and descending stairs. Conversely, in the normal hips, contact tended to be distributed across the entire acetabulum. During chair rise, contact in both groups was primarily in the posterior acetabulum, although it was more widely distributed in the normal hips than in the retroverted hips. The load was directed approximately superiorly during walking activities, ascending stairs and descending stairs, while the load was directed posteriorly during chair rise. These directions were more aligned with the surface normals of the contact area in the retroverted hips than in the normal hips. Therefore, the retroverted hips were able to sustain the applied load with lower contact stress and lower contact area than the normal hips as a result of a less distributed contact area that was aligned with the approximate direction of the applied load.

Differences in contact stress and contact area in the posterior regions may have important implications regarding the mechanisms of damage in retroverted hips and the preferred clinical treatment. Hips with retroversion often experience damage in the posterior acetabulum, which has been postulated to result from one of two mechanisms[36]. The first mechanism to consider is decreased contact area and a resulting elevated contact stress in the posterior acetabulum[7,14,15]. The preferred treatment for this mechanism of damage is periacetabular osteotomy[14,37]. Previous studies demonstrated decreased posterior coverage in retroverted hips, suggesting that retroverted hips have a smaller posterior contact area[12,13]. However, the results of the present study suggest that elevated posterior stresses alone may not be the mechanism of damage in retroverted hips. Specifically, contact stresses were not elevated in the posterior acetabulum of retroverted subjects, which suggests that periacetabular osteotomy may not be warranted or beneficial in subjects with retroversion from the point of view of reducing contact stress. The second mechanism that has been proposed is anterior femoroacetabular impingement, where damage is caused by collision of the femoral head–neck region against an abnormally prominent anterior acetabular rim[18–20]. The alternative treatment for this mechanism of damage is resection of the prominent anterior acetabular rim[14]. The present study did not evaluate the possible effects of impingement in normal subjects or retroverted patients, and this is a topic that warrants further investigation. In particular, other activities that will be more likely to produce impingement should be investigated.

Differences in predictions of contact stress between activities within each group illustrate the effects of the focused contact patterns in retroverted hips compared to the widely distributed contact patterns in normal hips [Fig. 4 and Supplementary Fig. S2]. This can be seen by comparing chair rise, where the load was directed posteriorly, to all other activities. Peak contact stress in the posterolateral region was larger during chair rise than during all other activities in retroverted hips, but this was not the case for normal hips. When the load was directed posteriorly during chair rise, the focused contact pattern in the retroverted hips caused higher peak stresses in the posterolateral region. However, the contact pattern was distributed across more of the acetabulum in the normal hips in all loading scenarios. Therefore, the posterior direction of the load during chair rise did not cause higher peak contact stresses during chair rise in the normal hips.

Several limitations in the present study warrant discussion. Because of the lack of a widely accepted morphological definition of acetabular retroversion, the spectrum of the morphological variation associated with the disease could have confounding effects on the results of this study. Acetabular retroversion is most often diagnosed using the crossover sign. Although the crossover sign is sensitive to the orientation of the pelvis with respect to the imaging plane, we controlled for pelvic inclination in the present study, which improves sensitivity of the crossover sign for diagnosis of retroversion to 96%[12,38]. It is worth noting that neither the Sharp's angle nor the acetabular index was significantly different between the two populations. Thus, it appears unlikely that abnormal acetabular inclination was the cause of medial contact in retroverted hips.

Similarly, this study did not evaluate femoral deformities as part of the patient selection criteria. Because femoral version in normal hips is correlated with acetabular version[39], abnormal femoral version in the retroverted hips may have influenced results. The retroverted hips in this study had larger alpha angles than the normal hips, suggesting a higher prevalence of cam-type deformities on the femur. With the possible exception of chair rise, the activities that were simulated in this study would not be expected to cause impingement even in hips with cam-type deformities. Nevertheless, confounding effects from the larger alpha angles in the retroverted group cannot be ruled out. In addition to the effects of isolated acetabular or femoral pathoanatomy, other differences in joint anatomy that were not quantified as part of the patient classification could have affected contact patterns.

The results of this study must be interpreted in light of the assumptions made in the FE models. Although cartilage material behavior is complex, it was represented as spatially homogeneous, isotropic and nearly linear hyperelastic[40]. These assumptions were justified because previous validation studies showed that FE predictions of contact stress and contact area using isotropic linear elastic and nearly linear hyperelastic cartilage constitutive models were in good agreement with experimental measurements[25,41]. A second limitation was the use of identical material coefficients for both groups. While there were no clinical or radiographic signs of cartilage degeneration in patients in the retroverted group, minor changes in cartilage material behavior may have occurred. Similarly, there is evidence that hips with abnormal bony anatomy exhibit abnormal gait patterns[42,43]. Identical loading scenarios were used for all subjects in this study because of the lack of literature data on gait in subjects with acetabular retroversion. This study was limited to predictions of contact stress and contact area. A large body of literature points to these variables as important in the pathogenesis of OA (e.g., Refs. [24,44,45]). However, other mechanical variables, such as the maximum shear stress, may be more important for predicting cartilage damage[46–48].The modeling requirements for accurate predictions of contact stress and contact area in the human hip have been established[25], but predicting other mechanical variables may require increased mesh resolution or more advanced constitutive models. Finally, the patient population used in this study was predominantly male. This bias is to be expected since the crossover sign and lower acetabular anteversion occur more frequently in men than in women[49,50].

In conclusion, this study demonstrated that hips with acetabular retroversion exhibit superomedial cartilage contact patterns during simulations of activities of daily living, while hips with normal bony anatomy exhibit widely distributed cartilage contact patterns. Further, the results suggest that elevated posterior stresses may not be the mechanism of damage in hips with retroverted acetabula.

Authors' contributions

CRH: patient recruitment, image data collection, image data segmentation, FE modeling, statistical analysis, manuscript preparation. EDC: image data segmentation, FE modeling, manuscript editing. AEA: study design, patient recruitment, image data collection, manuscript editing. MDH: image data collection, FE modeling, design of statistical methods, manuscript editing. BJE: FE modeling, manuscript editing. CLP: study design, patient recruitment, manuscript editing. JAW: study design, manuscript editing. CRH and JAW take responsibility for the integrity of this work.

Role of funding source

Funding was provided by the National Institutes of Health. The funding agency had no role in study design; data collection, analysis or interpretation; manuscript writing; or the decision to submit the manuscript.

Conflict of interest

The authors have no conflicts of interest.

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Supplementary data

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