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HIP

Open MRI assessment of anterior femoroacetabular clearance in active and passive impingement-provoking postures

**M. Mohtajeb,
J. Cibere,
M. Mony,
H. Zhang,
E. Sullivan,
M. A. Hunt,
D. R. Wilson**

From University of British Columbia, Vancouver, British Columbia, Canada

Aims

Cam and pincer morphologies are potential precursors to hip osteoarthritis and important contributors to non-arthritic hip pain. However, only some hips with these pathomorphologies develop symptoms and joint degeneration, and it is not clear why. Anterior impingement between the femoral head-neck contour and acetabular rim in positions of hip flexion combined with rotation is a proposed pathomechanism in these hips, but this has not been studied in active postures. Our aim was to assess the anterior impingement pathomechanism in both active and passive postures with high hip flexion that are thought to provoke impingement.

Methods

We recruited nine participants with cam and/or pincer morphologies and with pain, 13 participants with cam and/or pincer morphologies and without pain, and 11 controls from a population-based cohort. We scanned hips in active squatting and passive sitting flexion, adduction, and internal rotation using open MRI and quantified anterior femoroacetabular clearance using the β angle.

Results

In squatting, we found significantly decreased anterior femoroacetabular clearance in painful hips with cam and/or pincer morphologies (mean -11.3° (SD 19.2°)) compared to painfree hips with cam and/or pincer morphologies (mean 8.5° (SD 14.6°); $p = 0.022$) and controls (mean 18.6° (SD 8.5°); $p < 0.001$). In sitting flexion, adduction, and internal rotation, we found significantly decreased anterior clearance in both painful (mean -15.2° (SD 15.3°); $p = 0.002$) and painfree hips (mean -4.7° (SD 13°); $p = 0.010$) with cam and/pincer morphologies compared to the controls (mean 7.1° (SD 5.9°)).

Conclusion

Our results support the anterior femoroacetabular impingement pathomechanism in hips with cam and/or pincer morphologies and highlight the effect of posture on this pathomechanism.

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Introduction

Femoroacetabular impingement syndrome is diagnosed when symptoms (including hip and/or groin pain), signs (including positive impingement clinical tests such as the flexion, adduction, and internal rotation test), and radiological findings (bony morphologies) are all present.[1] The morphologies associated with femoroacetabular impingement (FAI) syndrome are potential precursors to hip osteoarthritis (OA),[2-6] and the most important contributors to non-arthritic hip pain.[7-10] FAI syndrome morphologies are categorized as cam (bony anomaly at the femoral head/head-neck junction), pincer (local or global acetabular overcoverage), and mixed (features of both cam and pincer morphologies).[2]

Correspondence should be sent to Dr David R Wilson; email: david.wilson@ubc.ca

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Table I. Participants' demographics.

Variable	CPM+ (n = 9)	CPM- (n = 13)	Control (n = 11)	p-value
Age, yrs, mean (SD)	51.1 (3.6)	48.7 (7.3)	48.3 (7.3)	0.598*
BMI, kg/m², mean (SD)	24.2 (4.5)	26.6 (4.1)	23.9 (3.2)	0.198*
Sex, %				
Male	33.3	38.5	18.2	0.633†
Female	66.7	61.5	81.8	
Morphology type, %				
Cam	22.2	30.8	N/A	N/A
Pincer	55.6	46.1	N/A	N/A
Mixed	22.2	23.1	N/A	N/A
Morphology severity, °				
α angle, mean (SD)	59.8 (9.9)	58.3 (9.7)	N/A	0.794‡
LCE angle, mean (SD)	35.4 (5.6)	34.6 (6.4)	N/A	0.758§
CPM laterality, %				
Unilateral	33.3	15.4	N/A	N/A
Bilateral	66.7	84.6	N/A	N/A
Pain laterality, %				
Unilateral	55.6	N/A	N/A	N/A
Bilateral	44.4	N/A	N/A	N/A

*Analyses of variance.
†Fisher's exact test.
‡Mann-Whitney U test.
§Independent-samples *t*-test.
CPM, cam and/or pincer morphologies; LCE, lateral centre edge; N/A, not applicable; SD, standard deviation.

It is unclear why some people with cam and/or pincer morphologies (CPM) have clinical symptoms and signs while others do not. Anterior abutment between the femoral head-neck junction and acetabular rim in cam hips leading to chondral abrasion and labral detachment, and linear contact between the femoral head-neck junction and acetabular rim in pincer hips affecting the labrum and leading to femoral leverage, are two proposed pathomechanisms in CPM hips. The abnormal contact between the femoral head-neck junction and the acetabular rim has been proposed to occur in hip flexion combined with internal/external rotation and adduction.[2] Direct 3D visualization of the flexed hip is required to verify these pathomechanisms and investigate why only some deformities lead to clinical symptoms, but this cannot be done with conventional imaging.

Direct visualization of hip impingement has been achieved with intraoperative observations in surgically dislocated hips[2,3] and with specialized imaging approaches, including open bore MRI,[11] 4D dynamic CT scanning,[12] and dual fluoroscopy with model-based tracking.[13] Two key limitations of work to-date are that all assessments were done for passive positioning of the hip, and that no comparisons were provided to CPM hips without symptoms. Impingement may be very different and more relevant to FAI pathomechanisms in weight-bearing postures that reflect physiological activity than in the passive postures that have been assessed to date. Squatting and sitting flexion, adduction, and internal rotation (FADIR) poses represent the final positions of active and passive maneuvers involving high hip flexion combined with rotation in the other two planes.

In this study, our research question was, "Is anterior femoroacetabular clearance (β angle) different between CPM hips with pain, CPM hips without pain, and control hips in squatting and sitting FADIR postures?"

Methods

Sample size calculation. Considering the β angle in 23 hips with FAI syndrome (mean 5° (standard deviation (SD 9°)) and 49 control hips (mean 30° (SD 9°)) in 90° of hip flexion reported previously,[11] the Cohen's D effect size was calculated to be 2.77°. We determined that at least four or five participants are required in each group using either the difference between independent means or Wilcoxon Mann-Whitney U test, to reach this effect size with a power of 0.95 and an α level of 0.05 (sample size was calculated using G*Power 3.1.9.7).[14]

Participants. We recruited 33 participants aged 28 to 56 years, including nine with cam and/or pincer morphologies and with pain (CPM+), 13 with cam and/or pincer morphologies and without pain (CPM-), and 11 controls (negative for pain and CPM) from the Investigation of Mobility, Physical Activity, and Knowledge Translation in Hip Pain (IMPAKT-HIP) cohort (Table I). The IMPAKT-HIP cohort is a population-based sample of 500 Caucasian people aged 20 to 49 years recruited through random-digit dialling of households in greater Vancouver, Canada.[15,16]

Hips were identified as having a cam morphology if the α angle[17] was greater than 55° on a standardized Dunn view radiograph.[18] Hips were identified as having a pincer morphology if the lateral centre edge (LCE) angle[19] was greater than 40° and/or a positive crossover sign was present on a standardized weightbearing anteroposterior radiograph.[20] Hips with both cam and pincer morphologies were classified as mixed. In the IMPAKT-HIP study, the presence of hip pain was defined as participant report of pain in the groin and/or upper thigh lasting for six weeks or more and/or for three or more episodes during the past 12 months. The study hip was defined as the hip with radiological CPM. If CPM was present in both hips, then the hip with more severe pain was defined as the study hip. If equal or no hip pain was reported, the study hip was randomly selected.

For our current study, we recruited participants from the original IMPAKT cohort a mean of 5.7 years (SD 0.5) after the original IMPAKT contact. Study hip, hip pain, and CPM were defined as they were in the original IMPAKT study. New exclusion criteria were used, including previous lower limb surgeries, injuries or any neurological conditions that affected everyday recreational or sporting activities over the past 12 months, a history of any inflammatory or autoimmune diseases, avascular necrosis of the hip, planned or previous lower limb joint replacement, or physician-diagnosed lower limb joint osteoarthritis. The Clinical Research Ethics Board of the University of British Columbia, Canada, approved the study, informed written consent was obtained from all participants, and the study was conducted in accordance with the Declaration of Helsinki.

β angle calculation. We scanned each participant's study hip in supine, squatting, and sitting FADIR poses using an upright open MRI scanner (MROpen; Paramed, Italy) to quantify anterior femoroacetabular clearance (β angle; Figure 1). Squatting is an active weightbearing posture that involves deep hip flexion, which is associated with impingement. Sitting FADIR is a passive posture with elevated hip angles that produces less clearance between the femur and the acetabulum than supine FADIR.[21] Supine represents a neutral reference for the hip joint position. Our protocol for these postures was as follows:

Squatting. Participants squatted to their maximum possible depth without rotating or lifting any part of their feet while their feet were oriented directly anteriorly and with the most lateral aspects of the toes 22 cm apart (Figure 2 (a)). A horizontal bar, the MROpen bed, and foam pads were positioned to stabilize the participants and minimize movement without providing weightbearing support. Participants were asked to hold their final squatting position for the duration of scanning (about 30 minutes).

Sitting FADIR. Participants were positioned in the scanner chair with the study hip at the scanner's centre. The leg was flexed to the limit of hip flexion, then moved to the limits of adduction and internal rotation (Figure 2 (b)). In patients with hip pain, the limit was defined as a posture producing a level of pain that could be tolerated for the duration of scanning (about 30 minutes). The knee was secured with several foam pads to minimize motion artifact.

At each posture, we acquired images in the plane parallel to the femoral neck and normal to the plane

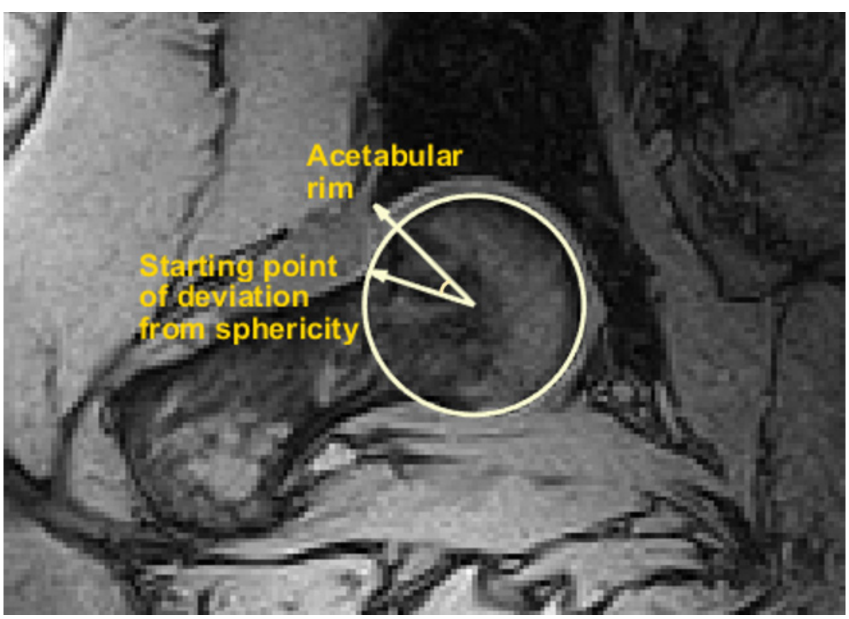

Fig. 1
Illustration of β angle in a control hip in the squatting posture in the α plane.

Fig. 2

Participants positioned in the a) squatting and b) sitting flexion, adduction, and internal rotation postures in the MROpen.

Table II. Sequence details of MROpen hip α plane scans used to calculate the β angle in the squatting/sitting flexion, adduction, and internal rotation (FADIR), MROpen hip/pelvis/knee scans used to define a hip coordinate system in the supine and calculate hip angles in the squatting/sitting FADIR.

Variable	Sequence	Matrix	Field of view	Slice thickness
MROpen hip α plane scans	GFE, short TE TE/TR = 8 ms/443 ms	256 × 256	25 cm	2.5 mm (0.5 mm gap)
MROpen hip sagittal scans	GFE, short TE TE/TR = 8 ms/627 ms	256 × 256	25 cm	2.5 mm (0.5 mm gap)
MROpen pelvis axial scans	GFE, TE/TR = 12 ms/370 ms	256 × 256	30 cm	2.5 mm (0.5 mm gap)
MROpen knee axial scans	GFE, TE/TR = 8 ms/650 ms	256 × 256	20 cm	2.5 mm (0.5 mm gap)

GFE, gradient field echo; MROpen, Open MRI Scanner (Paramed, Italy); TE, echo time; TR, repetition time.

formed by the femoral neck and the femoral shaft (α plane,[17] Table II).

We quantified clearance between the femoral head-neck contour and acetabular rim in the squatting and sitting FADIR postures by calculating the β angle on each slice (Figure 3). The β angle is the angle between a line drawn from the femoral head centre to the most lateral bony margin of the acetabular rim and a second line drawn from the centre of the femoral head to the starting point of deviation from sphericity in the femoral head-neck contour[11] (Figure 3). The minimum β angle for all slices was recorded for each posture. The rater was blinded to the α angle, LCE angle, and crossover sign.

Hip angles calculation. We calculated hip joint angles in supine, squatting, and sitting FADIR by scanning each participant's study side hip in the sagittal plane for each posture as well as the pelvis and study side knee in the axial plane in the supine posture (Table II).

We defined pelvis, femur, and hip joint coordinate systems based on bony landmarks in the pelvis and femur using the International Society of Biomechanics (ISB) recommendations.[22] To calculate hip joint angles in the squatting and sitting FADIR poses, femur and pelvis coordinate systems defined in the supine posture were transferred to the squatting and sitting FADIR postures by registering femur and acetabulum 3D point clouds generated from the segmented sagittal scans of the hip in the supine and squatting/sitting FADIR postures using the finite iterative closest point (ICP) algorithm.[23] Hip angles in each posture were calculated using the Grood and Suntay convention.[24] All calculations were performed using MATLAB (USA) and Statistics Toolbox Release 2017b (MathWorks, USA).

Statistical analysis. To assess the reliability of β angle measurements, we performed repeated scans at each posture on five participants in the squatting and sitting FADIR postures. To calculate the intrarater reliability of the β angle, the main reader measured the β angle for each participant at each posture twice using the repeated scans. To calculate the inter-rater reliability of the β angle, a second trained reader measured the β angles for each posture and each participant. We reported reliabilities using intraclass correlation coefficients (ICCs). ICC was calculated using the two-way mixed model to account for random subjects and fixed raters with absolute agreement type rather than consistency to reflect any differences that might be present among raters even with being correlated.

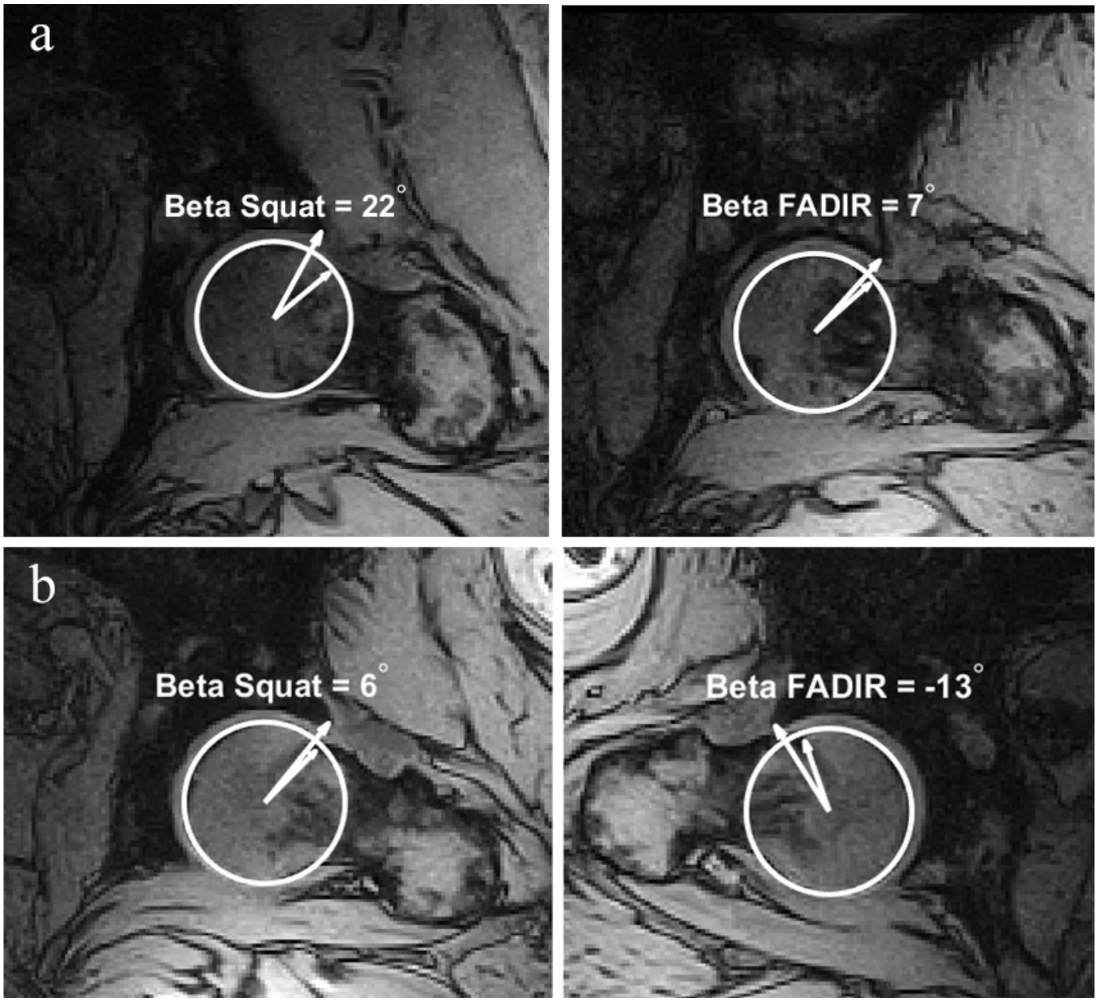

Fig. 3

Slices with the minimum β angle in the squatting and sitting flexion, adduction, and internal rotation postures in the MROpen for a) a control hip, and b) a cam and/or pincer morphology hip in the α plane.

We tested differences in sex distribution between CPM+, CPM-, and control groups using Fisher's exact test. We tested differences in age and BMI between CPM+, CPM-, and control groups using one-way ANOVA. We tested differences in the CPM severity, quantified by the α and LCE angles, between CPM+ and CPM- using independent-samples t-test or Mann-Whitney U test, based on data normality.

We tested our null hypothesis that there is no difference in β angle between CPM+, CPM-, and control hips using ANOVA or independent-samples Kruskal-Wallis tests, based on the normality of data, and for each posture (squat and sitting FADIR). If the omnibus tests were significant, post hoc independent-samples *t*-test or Dunn-Bonferroni pairwise comparison were run, based on the data normality to determine where the differences lie.

We tested differences in squat depth and hip angles at squatting/sitting FADIR postures between CPM+, CPM-, and control groups using ANOVA or independent-samples Kruskal-Wallis tests considering data normality. All statistical analyses were performed using IBM SPSS Statistics for Windows, version 27.0 (IBM, USA).

Results

We found no significant difference in sex distribution, age, BMI, α angle, and LCE angle between groups (Table I).

β angle. We found a significant difference in β angle between CPM+, CPM-, and control hips in the squatting posture ($p = 0.002$, independent-samples Kruskal-Wallis test) (Figure 4). The CPM + group had a significantly smaller minimum β angle (mean -11.3° (SD 19.2°)) than the CPM- (mean 8.5° (SD 14.6°)) ($p = 0.022$, Dunn-Bonferroni pairwise comparison) and control groups (mean 18.6° (SD 8.5°)) ($p < 0.001$, Dunn-Bonferroni pairwise comparison).

We found a significant difference in β angle between CPM+, CPM-, and control hips in the sitting FADIR posture ($p = 0.002$, ANOVA) (Figure 4). Both CPM + and CPM- groups had significantly smaller β angles (-15.2°

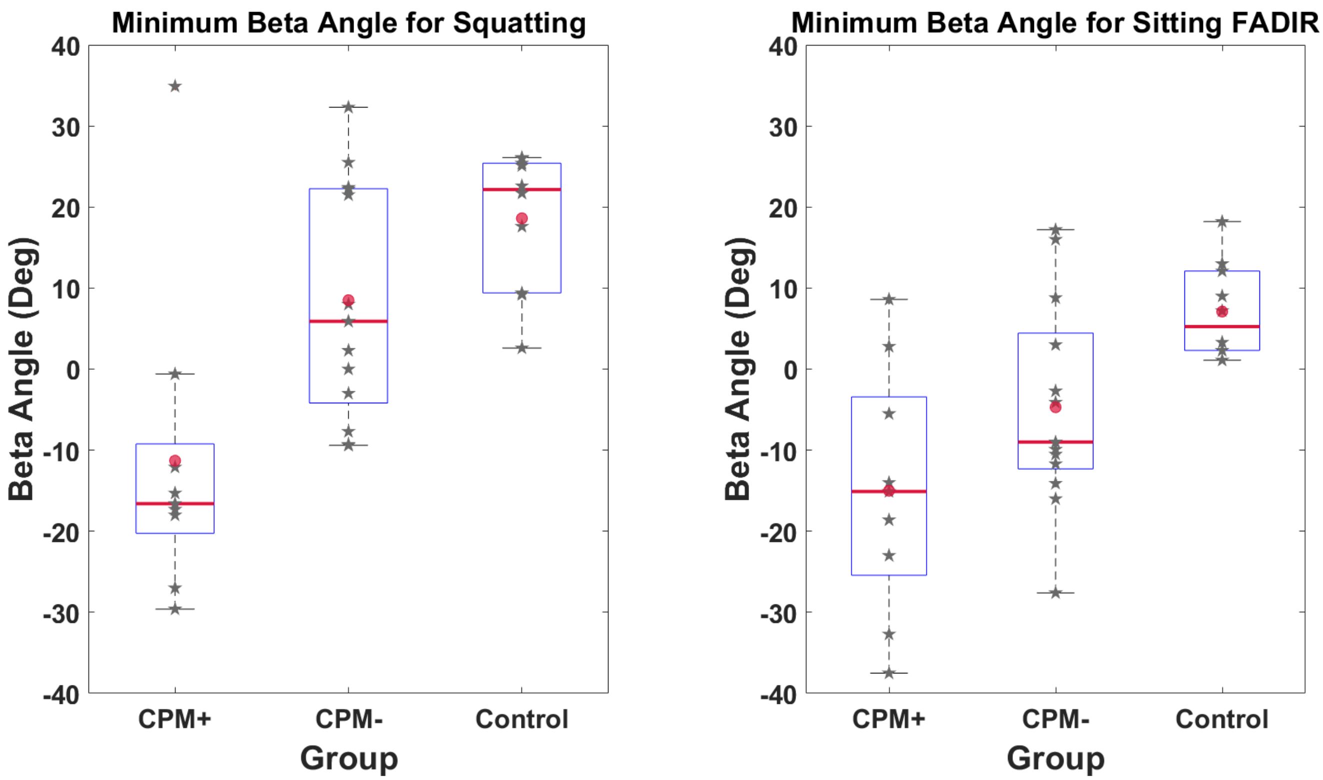

Fig. 4

Box plots of β angle in the squatting and sitting flexion, adduction, and internal rotation postures in the MROpen. The "★" symbol represents the β angle for each participant, and the "•" symbol represents the mean of the data.

(SD 15.3°) (p = 0.002, independent-samples t-test with equal variances not assumed) and -4.7° (SD 13°) (p = 0.010, independent-samples t-test with equal variances not assumed), respectively, than the control group (7.1° (SD 5.9°)).

Hip angles in the squatting and sitting FADIR postures. We found no significant difference in normalized squat depth between CPM+ (mean 23% (SD 4.9%)), CPM- (mean 22% (SD 4.2%)), and control (mean 21.3% (SD 4.6%)) groups (p = 0.602, ANOVA). In the squatting posture, we found no significant difference in hip flexion, internal/external rotation, and abduction/adduction angles between CPM+, CPM-, and control hips (p = 0.594, ANOVA; p = 0.373, independent-samples Kruskal-Wallis test; and p = 0.272, ANOVA, respectively) (Figure 5). In the sitting FADIR posture, we found no significant difference in hip flexion, internal/external rotation, and abduction/adduction between CPM+, CPM-, and control hips (p = 0.108, p = 0.505, and p = 0.848, respectively, all ANOVA) (Figure 5).

Reliability of β angle measurements in squatting and sitting FADIR. For squatting, we found ICCs of 0.98 (95% confidence interval (CI) 0.84 to 0.99) and 0.99 (95% CI 0.95 to 1.00) for intra- and inter-rater reliability of β angle measurements, respectively. For sitting FADIR, we found ICCs of 0.99 (95% CI 0.92 to 0.99) and 0.99 (95% CI 0.97 to 1.00) for intra- and inter-rater reliability of β angle measurements, respectively.

Discussion

In this study, we found that painful CPM hips had significantly less anterior femoroacetabular clearance than painfree CPM hips and control hips in active squatting, while we found no difference in clearance between the two CPM groups in passive sitting FADIR.

Our β angle measurements are comparable to a study of anterior femoroacetabular clearance in hip flexion in supine in an open MRI scanner.[11] That study's findings of a difference in β angles between control and FAI hips of about 25° in a supine posture with the hip at 90° of flexion and neutral internal/external rotation and abduction/adduction are comparable to our findings of a difference in β angles of about 30° in squatting. Our smaller β angles are likely due to differences in scan plane orientation and because our participants' hips were internally/externally rotated and abducted/adducted, while the earlier study positioned hips with neutral rotations in coronal and axial planes.

Our finding of more clearance in the CPM- hips than in the CPM+ hips in the active squatting but not in the passive sitting FADIR posture suggests that participants with CPM- limit their acetabular contact pressures

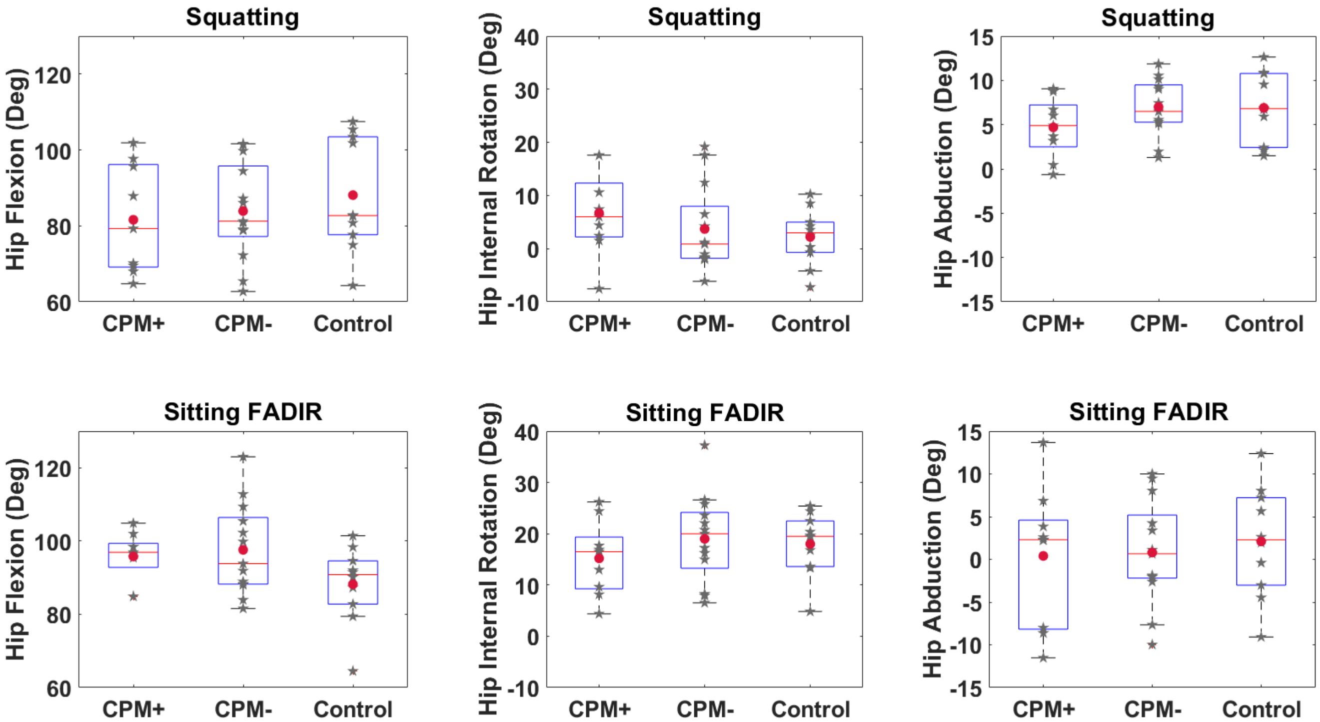

Fig. 5

Box plots of hip flexion, internal rotation, and abduction angles in the squatting and sitting flexion, adduction, and internal rotation postures in the MROpen. The "★" symbol represents hip angles for each participant, and the "•" symbol represents the mean of the data.

during this active posture because negative β angles are associated with elevated acetabular contact pressures.[25] Our measurements of hip angles showed that any differences in clearance are not due to differences in gross hip joint position. However, it is important to note that squatting and FADIR represent somewhat different hip positions, although they are both near the end of the range of hip flexion. The observed clearance differences could be due to muscular or capsuloligamentous strength differences between the CPM+ and CPM- groups, which could affect femoral head positioning inside the acetabulum. These findings suggest that during clinical examination of patients with FAI syndrome, functional testing like squatting in addition to passive testing might be beneficial.

Our finding of no difference in hip position between CPM+, CPM-, and control hips in squatting is consistent with earlier motion analysis studies of squatting in FAI hips.[26] One study found decreased pelvic sagittal range of motion in hips with FAI,[27] and our current finding of direct impingement between the femur and acetabulum in CPM+ hips during squatting provides an explanation for this reduced pelvic range of motion.

Strengths and limitations. One strength of this study is that we recruited our participants from a population-based cohort (the IMPAKT-HIP cohort). The other strength is that we assessed the abutment between the femoral head-neck contour and acetabular rim directly using the MROpen scanner.

One limitation of our study is the heterogeneity of morphology in the CPM+ and CPM- groups. This heterogeneity led to significant variability in the range of β angle, which is related to different engagement patterns between the femoral head-neck junction and acetabulum in these morphotypes in impingement-provoking postures. Cam morphology intrudes into the acetabulum leading to negative β angles, while for the pincer morphotype, impingement is due to the normal femoral head-neck junction abutting against the acetabular rim, which leads to a β angle near zero. We included both morphotypes in our cohort because anterior impingement between the femoral head-neck junction and the acetabular rim is a proposed pathomechanism in hips with cam and pincer morphologies regardless of the morphotype. The other limitation of our study is that we used radiographs acquired a mean of 5.7 years (SD 0.5) before our current study to categorize hips as CPM or normal. This limitation is unlikely to affect our findings because a study of cam hips found no clinically relevant change in femoral head-neck contour (α angle) over a mean of 5.3 years (2.5 to 7.2),[28] and similarly, LCE angle and crossover sign in dysplastic hips did not change over 20 years.[29] Categorizing hip morphologies based on plain radiographs may be another source of variability in β angle in our study. It is possible that the 2D radiographs may have led to some misclassifications of the 3D deformities that characterize FAI, even though radiographs are widely used to identify CPM.

In conclusion, CPM- hips have more clearance between the femoral head-neck contour and acetabular rim than CPM+ hips in the active squatting posture. In contrast, there is no difference in clearance between CPM+ and CPM- hips in the passive sitting FADIR posture. These differences may contribute to our understanding of why some CPM hips are painful, and others are not.

Take home message

- In squatting, we found significantly decreased anterior femoroacetabular clearance in painful hips with cam and/or pincer morphologies compared to pain-free hips with cam and/or pincer morphologies and controls.
- In sitting FADIR (flexion, adduction, and internal rotation), we found significantly decreased anterior femoroacetabular clearance in both painful and painfree hips with cam and/pincer morphologies compared to controls.

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Author information:

- M. Mohtajeb, BSc, MSc, PhD, Postdoctoral Research Fellow, Graduate Research Assistant, School of Biomedical Engineering, University of British Columbia, Vancouver, British Columbia, Canada; Center for Hip Health and Mobility, University of British Columbia, Vancouver, British Columbia, Canada.
- J. Cibere, MD, PhD, Senior Research Scientist, Associate Professor, Arthritis Research Centre of Canada, Richmond, British Columbia, Canada; Department of Medicine, University of British Columbia, Vancouver, British Columbia, Canada.
- M. Mony, BSc, In-House Clinical Research Associate II, Research Coordinator, Research Assistant, Arthritis Research Centre of Canada, Richmond, British Columbia, Canada.
- H. Zhang, PhD, Imaging Scientist
- E. Sullivan, BASc, Graduate Research Assistant
Center for Hip Health and Mobility, University of British Columbia, Vancouver, British Columbia, Canada.
- M. A. Hunt, BHK, MSc, MPT, PhD, Professor, Associate Dean, Motion Analysis and Biofeedback Laboratory, University of British Columbia, Vancouver, British Columbia, Canada; Department of Physical Therapy, University of British Columbia, Vancouver, British Columbia, Canada.
- D. R. Wilson, BEng, DPhil, Professor, Center for Hip Health and Mobility, University of British Columbia, Vancouver, British Columbia, Canada; Department of Orthopaedics, University of British Columbia, Vancouver, British Columbia, Canada.

Author contributions:

- M. Mohtajeb: Project administration, Conceptualization, Investigation, Methodology, Visualization, Formal analysis, Validation, Writing – original draft, Writing – review and editing.
- J. Cibere: Conceptualization, Supervision, Resources, Writing – review and editing.
- M. Mony: Resources.
- H. Zhang: Conceptualization, Methodology, Writing – review & editing.
- E. Sullivan: Validation.
- M. A. Hunt: Conceptualization, Resources, Writing – review & editing.
- D. R. Wilson: Project administration, Conceptualization, Supervision, Resources, Investigation, Methodology, Writing – review & editing.

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