Association Between Hip Translation and Hip Rotation and Anatomy

A Pilot Quasi-static MRI Study

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Background: There is little known about translation of the hip and the relationship with hip rotation and morphology in asymptomatic patients.

Hypotheses: (1) Femoral head would exhibit significant translations in asymptomatic hips, (2) femoral head translations would correlate to femoral rotations, and (3) range of femoral head translations would correlate to hip morphology.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: A total of 11 individuals (age, 23-47 years; 64% female) with asymptomatic hips underwent hip magnetic resonance imaging (MRI) in the following postures: neutral (supine), midflexion, maximum-flexion, internal rotation, internal rotation + midflexion, internal rotation + maximum-flexion, adduction, flexion-abduction-external rotation (FABER), extension, and lateral abduction. All rotations were passive. MRI-generated 3-dimensional hip models were used to quantify femoral rotations and translations. Femoral head diameter, acetabular diameter, lateral center-edge angle, alpha angle, femoral anteversion, acetabular version and inclination, and neck-shaft angle were measured from MRI. A *t* test was used if measured translations were statistically significant. Linear regression was used to assess the associations between translation and rotation. Pearson correlation was used to assess the relationships between hip anatomy and range of femoral head translations.

Results: In all tested positions, the femoral head translated anteriorly by 2 ± 1 mm (maximum 5 mm, $P < .001$), posteriorly by 1 ± 1 mm (maximum 6 mm, $P < .001$), superiorly by 2 ± 2 mm (maximum 7 mm, $P < .001$), inferiorly by 2 ± 2 mm (maximum 6 mm, $P < .001$), laterally by 1 ± 1 mm (maximum 4 mm, $P < .001$), and medially by 2 ± 1 mm (maximum 5 mm, $P < .001$), relative to the rested supine position. Femoral flexion was associated with posterior translation of the femoral head ($P = .038$). Femoral abduction was associated with medial translation of the femoral head ($P = .042$). Higher femoral anteversion and smaller alpha angle were associated with a higher total magnitude of femoral head translation in the anterior-posterior direction ($P < .04$). Smaller femoral anteversion, higher acetabular inclination, smaller lateral center-edge angle, and lower neck-shaft angle were associated with a higher total magnitude of femoral head translation in the superior-inferior direction ($P \leq .03$).

Conclusion: Our study demonstrated that, during passive physiologic movement, asymptomatic hips on average translated up to 2 mm (with up to 7 mm maximum translation in some positions), which is potentially related to hip rotations and morphology. Further investigations are warranted to understand the normal and pathologic hip translations and their impact on hip function (ie, instability and impingement).

Keywords: anatomy; femoroacetabular impingement; hip; magnetic resonance imaging; morphology; translation

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Whereas the hip is typically thought of as a ball-and-socket joint with purely rotational motion around a fixed center, a growing number of studies have shown significant femoral head translation in both cadaveric models and in vivo. Previous cadaveric analyses suggested that damage to soft tissue components of the acetabulum increases femoral head translation.[8,12,26,30,38] Several in vivo studies analyzed femoral head translation and rotation in specific

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athletic movements to investigate their influence on the development of hip disease.[3,6,11,15] Femoracetabular impingement (FAI) syndrome is of particular interest to this new hip joint theory because of FAI's association with early onset hip pain and secondary osteoarthritis in athletically active young adults.[4,14,21,25,33] Extensive biomechanical studies were conducted to investigate the physiologic movements that cause impingement symptoms among these hip morphologies, revealing repetitive low impact loading during flexion and internal rotation as a primary cause.[18] Elucidating the translational and rotational profile of the femoral head in the acetabular socket during these physiological movements would provide new insights regarding the etiology of FAI and other hip diseases.

While investigations examining the biomechanical profile of the hip joint grow in number, methods for analyzing hip translation vary significantly across the literature. Techniques include dynamic fluoroscopy,[20,24,26,34] motion capture devices,[6,8,16] musculoskeletal models,[17,39] dynamic ultrasound,[10,19,23] roentgen stereophotogrammetric analysis,[12] plain radiograph analysis,[7] and 3-dimensional (3-D) segmentation of computed tomography or magnetic resonance imaging (MRI).[1,2,9,11,15,30,31,35] Many studies have utilized these tools to compare diseased hips with native controls. To our knowledge, however, no study to date has established how in vivo hip translation and rotation manifest in asymptomatic native hips undergoing a variety of physiologic movements.

The purpose of this study was to assess the detailed motion of the hip joint in 6 degrees of freedom across a range of physiologically relevant movements using MRI scan and 3-D analysis in a cohort of volunteers with asymptomatic hips. We hypothesized that (1) the femoral head would exhibit substantial translations in asymptomatic hips, (2) there would be significant correlations between femoral head translations and femoral rotations, and (3) there would be significant correlations between range of femoral head translations and key morphological features of the hip joint.

METHODS

Patients

Following institutional review board approval (IRB-P00031280), 11 healthy volunteers with asymptomatic hips were recruited to participate in this study. Patients were included if they were 18 to 50 years old with a body mass index of $\leq$30 kg/m^2. Patients were excluded if they were pregnant or had a history of growth-related disorders, diseases of bone and connective tissue, neuromuscular diseases, previous hip surgery, any history of hip pain, degeneration and arthritis, and self-reported restricted joint range of motion of the hip and knee. Eligible individuals provided consent before participating in the study. An experienced fellowship-trained musculoskeletal radiologist (S.B.) reviewed all MRIs and confirmed lack of any hip pathology based on several imaging phenotypes assessed on the MRI.

Magnetic Resonance Imaging

After enrollment, patients underwent MRI using a coronal T1-weighted VIBE Dixon sequence that was optimized to have a large field of view (FOV), high spatial resolution, and short acquisition time (repetition time/echo time = 4/1.23, 420 × 420 FOV, 1.1-mm slice thickness, 320 × 256 matrix). The imaging was done in a Siemens 3T Skyra scanner using an 18-channel flex body coil. Dixon techniques present many advantages compared with other fat suppression techniques including (1) the robustness of fat signal suppression, (2) the possibility to combine these techniques with all types of sequences (gradient echo, spin echo) and different weightings (T1-, T2-, proton density-, intermediate-weighted sequences), and (3) the availability of images both with and without fat suppression from a single acquisition. The generation of these sequences is helpful to accurately delineate the boundaries of the anatomic structures during segmentation.

Patients were scanned under 10 positions (Table 1). All positions were passive and guided by a trained member of the team (S.H.). Once the limbs were in position, they were rested on foam wedges and fixed with straps to avoid motion artifacts and minimize muscle activity. The positions were set based on patients' physiologic range of motion, comfort, and ability to fit inside the scanner. The achieved range of rotation was measured from MRI as described below. The neutral scan covered the complete femurs and pelvis, while the other scans covered solely the pelvis and proximal femurs. The mean scan time, including positioning, was 52 ± 11 minutes. MRI scans were reviewed by an experienced fellowship trained

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Ethical approval for this study was obtained from the Boston Children's Hospital (IRB-P00031280).

TABLE 1
Studied Positions[a]

Position	Body Position	Studied Leg Position	Studied Hip Position	Contralateral Leg Position	Contralateral Hip Position
Neutral	Supine	Straight knee	Neutral	Straight knee	Neutral
Midflexion	Supine	Flexed knee	Flexed (~30°)	Straight knee	Neutral
Maximum flexion	Supine	Flexed knee	Flexed[b]	Straight knee	Neutral
Internal rotation	Supine	Straight knee	Internally rotated[b]	Straight knee	Neutral
Internal rotation + midflexion	Supine	Flexed knee	Flexed (~30°) + internally rotated[b]	Straight knee	Neutral
Internal rotation + maximum flexion	Supine	Flexed knee	Flexed[b] + internally rotated[b]	Straight knee	Neutral
Adduction	Supine	Straight knee[c]	Adducted[b]	Straight knee	Neutral
FABER	Supine	Flexed knee	FABER (mimicking the clinical examination)	Straight knee	Neutral
Extension	Quadruped	Straight knee	Extended[b]	Flexed knee	Flexed
Lateral abduction	Lateral decubitus	Straight knee	Abducted[b]	Straight knee	Neutral

[a] FABER, flexion-abduction-external rotation.

[b] To the maximum possible level based on patient comfort and ability to fit inside the magnet.

[c] Crossing over the contralateral leg.

pediatric musculoskeletal radiologist (S.B.) to evaluate all patients for occult hip pathology.

Image Processing

An orthopaedic surgeon (A.E.) manually segmented the pelvis and femurs for all scans and patients using a commercial image processing software (Mimics, Materialise). The segmentations were then reviewed by 2 independent investigators (S.H. and C.M.), as shown in Figure 1. The segmented masks were then used to reconstruct 3-D geometries for each bone (Figure 1). The reconstructed geometries were then imported to 3-matic software (Materialise) to conduct the measurements. The reconstructed pelvis and femurs from the neutral scan were translated into an anatomic coordinate system based on the International Society of Biomechanics recommended coordinate system.[36] A best-fit sphere was used to find the center of the femoral head which was used as the origin of the femoral coordinate system (Figure 1). For each participant, the reconstructed 3-D models of the hip from all other motions were then superimposed on the neutral models by registering the pelvises to the neutral pelvis using a N-point registration algorithm (Figure 1). The superimposed femurs were then used to measure femoral translations (in millimeters) and rotations (in degrees) relative to the neutral femur. To further assess the extent of femoral head translation independent of patient size, we normalized the translations to the diameter of the acetabulum, measured in 3-D using the best-fit sphere, and reported them as percentage of acetabulum diameter. Neutral MRI scans were also used to measure femoral anteversion, neck-shaft angle, alpha angle, lateral center-edge angle, and acetabular inclination following established techniques. Segmentation and analysis were performed on deidentified MRI scans to minimize bias. All the measurements were repeated by a second investigator (C.M.) to document measurement accuracy (mean absolute error of <1 mm and <3°) and interrater reliability (intraclass correlation coefficient of 0.87 for translation and 0.92 for rotation).

Statistical Analysis

Descriptive statistics and graphs were used to characterize the femoral head translation. To test our first hypothesis, the mean femoral head translations in each direction (ie, anterior, posterior, inferior, superior, medial, and lateral) across all tested positions were calculated and tested to see whether they were significantly different from 0 (no translation) using *t* tests. To test the second hypothesis, bivariate linear regression was used to assess the associations between translation (continuous dependent variable) and rotation (continuous independent variable). Separate analysis was done for each pair of translations and uniplanar rotations (eg, anterior-posterior translation versus flexion-extension). Next, a multivariate linear regression was used to assess the relationships between translation (continuous dependent variable) and multiplanar rotation (continuous independent variables). For this analysis, all 3 rotations (ie, flexion-extension, abduction-adduction, and internal-external rotations) were entered into the model as independent variables. The rotations with a P value of $>.1$ were eliminated using a backward stepwise procedure. To test the second hypothesis, all the rotations and translations for all the positions were pooled (n = 99). To test the third hypothesis, Pearson correlation was used to assess the relationships between hip anatomy and range of femoral head translations. For this analysis, the range of translation for each direction was calculated (eg, anterior-

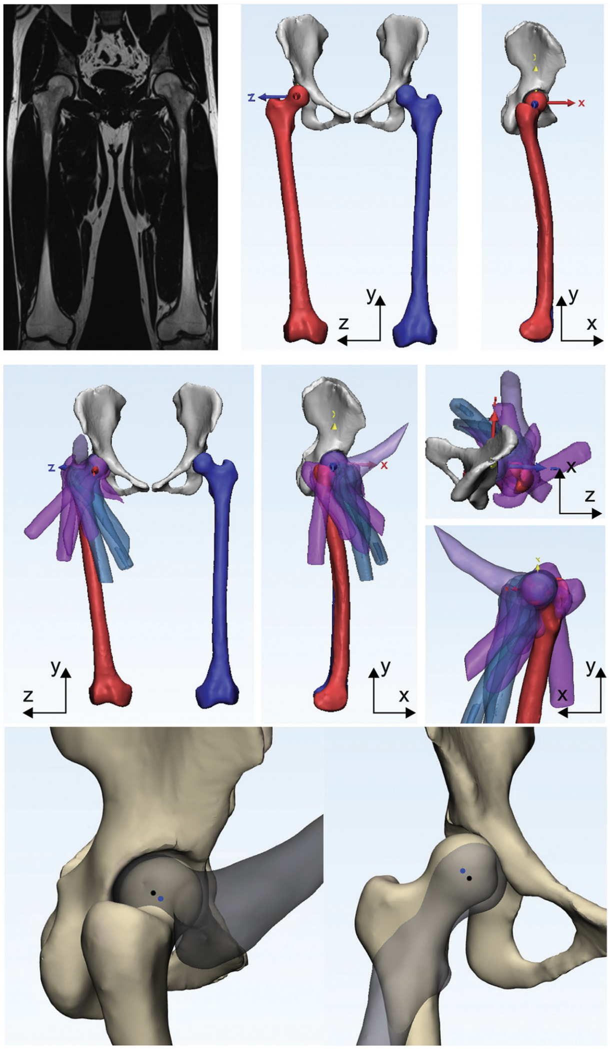

Figure 1. Top row, Development of 3-D models from MRI scans and definition of anatomic coordinate system (+x, anterior; +y, superior; +z, lateral). Middle row, Model registration to calculate the relative rotation and translation of the femur with respect to the neutral position. The transparent femora are segmented femora from all different positions, which have been registered to the neutral position by matching the pelvis models. The registered and superimposed 3-D femur models were then used to calculate the femoral rotation and translation in the same coordinate system as the neutral models. Bottom row, Hip translation was measured as the distance of between the femoral head center during rotations (black) and femoral head center in the neutral position (blue). 3-D, 3-dimensional; MRI, magnetic resonance imaging.

posterior translation range was calculated as maximum anterior translation-maximum posterior translation across all tested positions for each participant). This led to a sample size of 11 per Pearson correlation tests. All *P* values were 2-sided and considered statistically significant at $\alpha = .05$. The analyses were done using SPSS (Version 27, IBM).

RESULTS

Out of 11 recruited participants, there were 4 male patients and 7 female patients; 10 right hips and 1 left hip were assessed. The baseline characteristics and anatomic indices for the patients are presented in Table 2. The achieved range of rotations and translations across all participants are presented in Table 3. On average, the femoral head translated anteriorly by 2 ± 1 mm, posteriorly by 1 ± 1 mm, superiorly by 2 ± 2 mm, inferiorly by 2 ± 2 mm, laterally by 1 ± 1 mm, and medially by 2 ± 1 mm. These translations were all statistically significant compared with no translation (0 mm; $P < .001$ for all comparisons). The distribution of the femoral head translation in the sagittal and coronal planes is presented in Figure 2.

The bivariate regression coefficients for associations between femoral rotations and translations are presented in Table 4. Among all tested associations, only those between femoral flexion-extension and anterior-posterior translation and between abduction-adduction and lateral-medial translations were statistically significant. In general, femoral flexion was associated with posterior translation of the femoral head ($P = .038$). Similarly, femoral abduction was associated with medial translation of the femoral head ($P = .042$). The multivariate analysis resulted in the same findings, with no additional rotational predictors remaining included in the models, resulting in the same regression coefficients (Table 4).

The correlation coefficients for associations between range of femoral head translations and hip anatomy are presented in Table 5. In general, higher femoral anteversion and smaller alpha angle were associated with higher range of femoral head translation in the anterior-posterior direction ($P < .04$). Smaller femoral anteversion, higher acetabular inclination, smaller lateral center-edge angle, and lower neck-shaft angle were associated with higher range of femoral head translation in the superior-inferior direction ($P \leq .03$). There were no significant associations between quantified hip anatomic features and range of femoral head translation in the lateral-medial direction ($P > .1$).

DISCUSSION

The major finding of our study was significant translational motion in all 3 anatomic planes in native asymptomatic hips ($P < .001$), supporting our first hypothesis. From all tested associations between femoral rotations and translations, we only saw significant associations between flexion and posterior translation ($P = .038$) and between abduction and medial translation ($P = .042$), partially supporting our second hypothesis. From all the tested associations between range of translations and hip anatomy, only smaller femoral anteversion ($P = .009$), higher acetabular inclination ($P = .028$), smaller lateral center-edge angle ($P = .024$), and lower neck-shaft angle ($P = .03$) were associated with higher range of femoral head translation in the superior-inferior direction. Increased femoral anteversion ($P = .024$) and reduced alpha angle ($P = .034$) were

TABLE 2
Baseline Characteristics and Anatomic Indices[a]

Index	Mean ± SD	Range
Age, y	30 ± 7	23 to 47
Mass, kg	70.5 ± 14.1	54.4 to 92.7
Height, m	1.7 ± 0.1	1.5 to 1.9
BMI, kg/m^2	24.8 ± 2.4	20.8 to 28.5
Femoral head diameter, mm	44 ± 5	37 to 51
Acetabular diameter, mm	54 ± 5	48 to 62
Femoral anteversion, deg	8 ± 7	-34 to 18
Acetabular version, deg	19 ± 7	10 to 27
Acetabular inclination, deg	48 ± 4	39 to 57
Lateral center-edge angle, deg	33 ± 6	27 to 46
Neck-shaft angle, deg	135 ± 4	130 to 141
Alpha angle, deg	47 ± 13	29 to 69

[a] BMI, body mass index.

associated with increased anterior-posterior femoral head translation, partially supporting our third hypothesis.

Our current findings of significant femoral head translations during rotation are in general agreement with those reported in previous studies of asymptomatic[1,10,19,23,30,38] and pathologic[1,9,15,20,23,24,31] hips, with the exception of smaller lateral translations seen in this in vivo study compared with a cadaveric study.[30] This discrepancy can be attributed to the differences in tested range of hip rotation as well as the differences in hip stability and integrity in live individuals compared with dissected cadaveric joints. In a cadaveric analysis of 36 hip positions in cadavers using optical-based kinematic assessment, Safran et al[30] reported mean maximum femoral head translations of 2 ± 2 mm (anterior), 3 ± 2 mm (posterior), 2 ± 2 mm (superior), 4 ± 2 mm (inferior), 6 ± 4 mm (lateral), and 0 ± 3 mm (medial). Similarly, several studies of hips with FAI and dysplasia have also reported substantial translations of the femoral head ranging from <1 to 4 mm of translation in the anterior-posterior, medial-lateral, and inferior-superior directions (depending on the position and measurement modality).[1,9,15,20,23,24,31] Our current findings corroborate those previous reports and highlight substantial femoral head translations even in asymptomatic hips. Such translations can significantly influence hip articulations and potential instability and impingement, which cast doubts on the accuracy and reliability of the existing hip impingement analysis platforms, which do not consider translation.

Although we did not find any associations between femoral rotations and femoral head translations in the superior-inferior direction, there were significant associations between flexion and posterior translation and between abduction and medial translation of the femoral head. These observations are in part consistent with previous reports of posterior, medial, and inferior translations during FABER examination.[1,7,9,13,20,22,28] Whereas these agreements support potential links between hip rotations and translations, the fact that flexion and abduction rotations were only able to explain 4% (linear regression R^2 = 0.04) of the variations seen in the posterior and medial translations, respectively, highlights the complexity of the interactions between hip rotations and translations. Further studies on larger cohorts are essential to better investigate these relationships with adequate statistical power to adjust for potential confounders.

Most interestingly, we saw significant associations between some of the key morphological features of the hip that are known to be involved in FAI and hip instability. With regard to the anterior-posterior translation, we saw increased femoral anteversion correlating with increased translation. This is consistent with the effect of femoral anteversion on increased hip instability, in particular in the anterior direction.[32] We also saw decreased anterior-posterior translation with increasing alpha angle, which could be due to limited space available in the acetabulum for a more aspherical femoral head to translate. A small study by Ng et al[27] found that decreased neck-shaft angle increases joint stability and shear stress across the acetabulum regardless of the presence of cam deformity. Their findings are consistent with our own, as smaller neck-shaft angles likely result in higher friction between the femoral head and acetabulum, which would minimize the extent of femoral head translation. On the acetabular side, we found that increased acetabular inclination and decreased lateral center-edge angle correlated with increased femoral head translation in the superior-inferior direction. Both increased acetabular inclination and decreased lateral center-edge angle have consistently shown to result in hip instability.[32] A more vertical and shallower acetabulum will be less effective in limiting femoral head translation, particularly in the superior-inferior direction.

TABLE 3
Achieved Range of Motion[a]

Motion	Range
Extension-flexion	Up to 25° (extension)-up to 112° (flexion)
Adduction-abduction	Up to 55° (adduction)-up to 53° (abduction)
External rotation-internal rotation	Up to 56° (external rotation)-up to 52° (internal rotation)
Posterior-anterior translation	Up to 6 mm or 11% (posterior)-up to 5 mm or 10% (anterior)
Inferior-superior translation	Up to 6 mm or 12% (inferior)-up to 7 mm or 11% (superior)
Medial-lateral translation	Up to 5 mm or 9% (medial)-up to 4 mm or 7% (lateral)

[a] Femoral head translations are presented in millimeters and as percentage of acetabulum diameter.

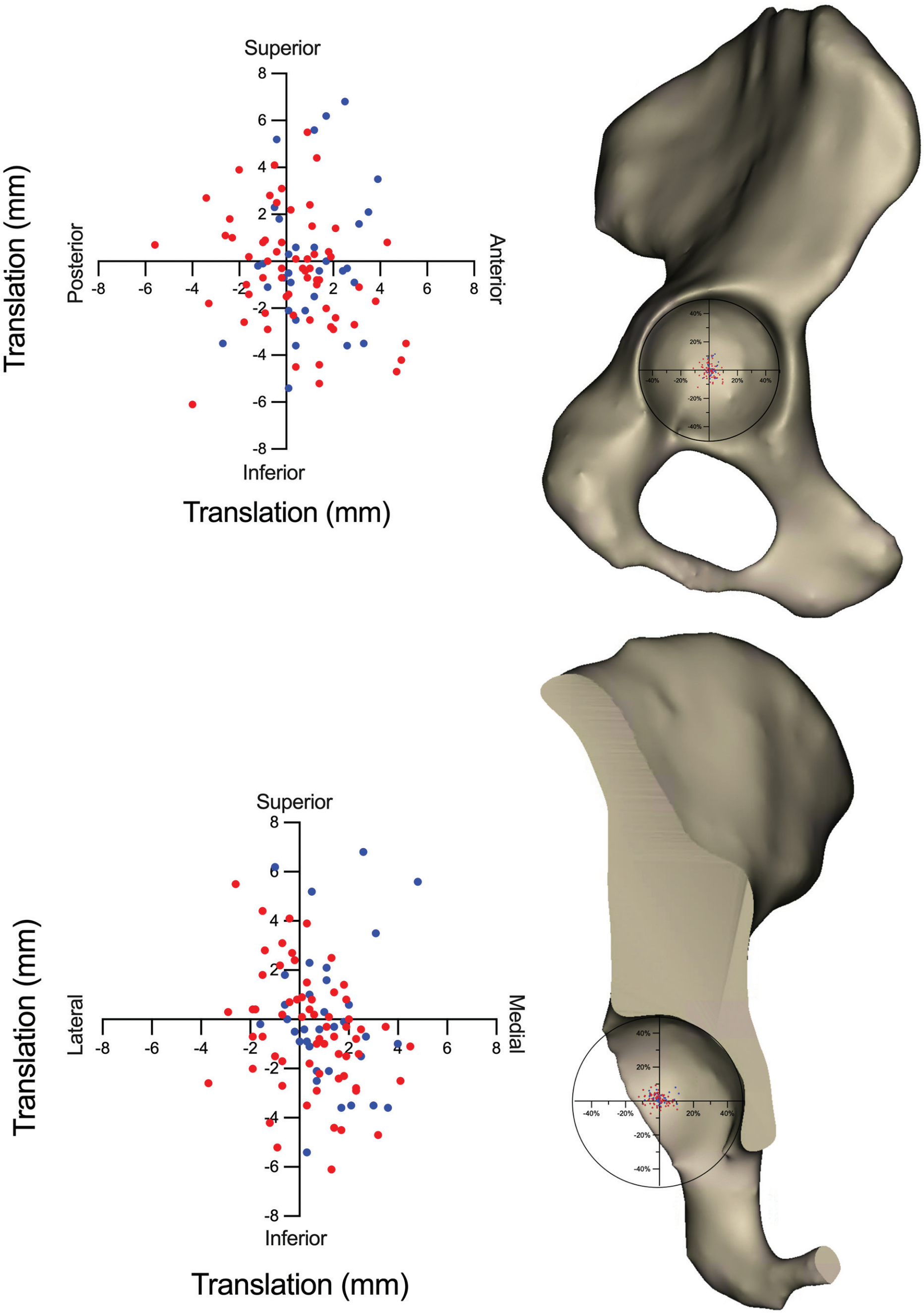

Figure 2. Distribution of femoral head translation in the sagittal (top row) and coronal (bottom row) planes across all positions. The center of the coordinate system is located at the center of the femoral head. Blue dots represent male patients and red dots represent female patients. The normalized translations (percentage of acetabular diameter) are presented inside the acetabulum model.

Limitations

There are several limitations to be considered when interpreting the current results. First, the data were collected on a small number of participants with asymptomatic hips. Further, the small sample size may have resulted in skewed anatomic measurements, such as smaller than mean femoral head diameter[37] and femoral version,[5] which in turn may have impacted the observed associations with femoral head translations. Future large-scale cohorts of participants with normal, FAI, and unstable (eg, dysplasia) hips are required to further investigate the normal and pathologic hip translations and their associations with hip rotations and anatomy. Second, the motions were all

TABLE 4
Regression Coefficient (β [95% CI], R^2) for Associations Between Femoral Rotations and Femoral Head Translations[a]

	Posterior (-)-Anterior (+) Translation	Inferior (-)-Superior (+) Translation	Medial (-)-Lateral (+) Translation
Extension (-), flexion (+)	β = -0.02 (-0.03 to 0.00) R^2 = 0.04 ***P* = .038**	β = 0.00 (-0.02 to 0.02) R^2 = 0.00 *P* = .702	β = -0.00 (-0.01 to 0.01) R^2 = 0.00 *P* = .724
Adduction (-), abduction (+)	β = -0.02 (-0.01 to 0.04) R^2 = 0.02 *P* = .145	β = -0.01 (-0.04 to 0.02) R^2 = 0.00 *P* = .541	β = -0.02 (-0.04 to 0.00) R^2 = 0.04 ***P* = .042**
External rotation (-), internal rotation (+)	β = 0.01 (-0.01 to 0.02) R^2 = 0.01 *P* = .303	β = -0.003 (-0.01 to 0.02) R^2 = 0.01 *P* = .750	β = -0.01 (-0.02 to 0.01) R^2 = 0.01 *P* = .353

[a]Significant correlations are bold. CI, confidence interval.

TABLE 5
Pearson Correlation Coefficient (*r* [95% CI]) for Associations Between Femoral Head Range of Translations and Hip Anatomy[a]

	Posterior-Anterior Translation Range	Inferior-Superior Translation Range	Medial-Lateral Translation Range
Femoral head diameter	*r* = -0.41 (-0.81 to 0.25) *P* = .212	*r* = -0.05 (-0.63 to 0.56) *P* = 877	*r* = -0.11 (-0.67 to 0.52) *P* = .748
Acetabular diameter	*r* = -0.51 (-0.85 to 0.13) *P* = .107	*r* = -0.10 (-0.66 to 0.53) *P* = .769	*r* = 0.02 (-0.59 to 0.61) *P* = .954
Femoral anteversion	*r* = 0.67 (0.12 to 0.91) ***P* = .024**	*r* = -0.74 (-0.93 to -0.26) ***P* = .009**	*r* = -0.51 (-0.85 to 0.12) *P* = .105
Acetabular version	*r* = 0.25 (-0.41 to 0.74) *P* = .459	*r* = -0.07 (-0.64 to 0.55) *P* = .830	*r* = -0.36 (-0.31 to 0.79) *P* = .278
Acetabular inclination	*r* = -0.18 (-0.70 to 0.47) *P* = .594	*r* = 0.66 (0.09 to 0.90) ***P* = .028**	*r* = 0.14 (-0.49 to 0.69) *P* = .672
Lateral center-edge angle	*r* = -0.22 (-0.73 to 0.43) *P* = .509	*r* = -0.67 (-0.91 to -0.12) ***P* = .024**	*r* = -0.43 (-0.82 to 0.23) *P* = .188
Neck-shaft angle	*r* = -0.06 (-0.63 to 0.56) *P* = .869	*r* = -0.65 (-0.89 to -0.08) ***P* = .030**	*r* = -0.26 (-0.74 to 0.40) *P* = .437
Alpha angle	*r* = -0.64 (-0.89 to 0.06) ***P* = .034**	*r* = -0.14 (-0.68 to 0.50) *P* = .689	*r* = -0.22 (-0.72 to 0.44) *P* = .515

[a]Significant correlations are bold. CI, confidence interval.

passive, which may have resulted in different motion patterns than those seen during active movements. The choice of passive movement was made to replicate clinical examination conditions and to accommodate limited space and relatively long periods of postural pause during MRI. The muscle activation could have altered joint stability,[29] thus leading to different translations. Active positions would require that patients be of specific physique to maintain said positions, which may introduce sample bias. Third, all the motions were nonweightbearing, which may have influenced the observed translations. While techniques such as biplanar fluoroscopy and dynamic ultrasound imaging can be used to measure translation during active weightbearing motions, their associated high radiation exposure (ie, fluoroscopy) and low reproducibility (ie, ultrasound) limit their utility. Last, considering the pilot nature of this study, no a priori power analysis and adjustment for multiple testing was done. This needs to be considered when interpreting the findings. Future studies with larger sample size are required to confirm the reported findings.

CONCLUSION

The current findings reveal that during passive physiologic movement, the asymptomatic hips on average translated up to 2 mm (with up to 7 mm maximum translation in some positions), which is potentially related to hip rotations and morphology. These translations can significantly influence the femur's articulation inside the acetabulum, which would have direct impact on hip stability and impingement. Further investigations are warranted to understand the normal and pathologic hip translations and their impact on hip function (ie, instability and impingement).

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