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RESEARCH ARTICLE

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Greater hip abductor size in prearthritic patients with developmental dysplasia of the hip versus femoroacetabular impingement

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Abstract

Developmental dysplasia of the hip (DDH) and femoroacetabular impingement (FAI) are common hip pathologies and important risk factors for osteoarthritis, yet the disease mechanisms differ. DDH involves deficient femoral head coverage and a shortened abductor moment arm, so this study hypothesized that the cross-sectional area (CSA) of the gluteus medius/minimus muscle complex and the stabilizing iliocapsularis muscle would be larger in DDH versus FAI, without increased fatty infiltration. A longitudinal cohort identified prearthritic patients with DDH or FAI who underwent imaging before surgery. Patients with DDH and FAI (Cam, Pincer, or Mixed) were 1:1 matched based on age, sex, and body mass index. Magnetic resonance imaging was used to measure the gluteus medius/minimus complex and iliocapsularis in two transverse planes. Amira software was used to quantify muscle and noncontractile tissue. Paired samples *t*-tests were performed to compare muscle size and composition ($p < 0.05$). There were no differences in the iliocapsularis muscle. Patients with DDH had significantly larger CSA of the gluteus medius/minimus complex at both transverse planes, and the noncontractile tissue proportion did not differ. The mean difference in overall muscle CSA at the anterior inferior iliac spine was $4.07 \pm 7.4\ cm^2$ ($p = 0.005$), with an average difference of 12.1%, and at the femoral head this was $2.40 \pm 4.37\ cm^2$ ($p = 0.004$), with an average difference of 20.2%. This study reports a larger CSA of the gluteus medius/minimus muscle complex in DDH compared to FAI, without a difference in noncontractile tissue, indicating increased healthy muscle in DDH.

KEYWORDS

developmental dysplasia of the hip, femoroacetabular impingement, hip abductors, iliocapsularis, noncontractile tissue

1 | INTRODUCTION

Both developmental dysplasia of the hip (DDH) and femoroacetabular impingement (FAI) are common hip pathologies that often present in young adults and are important risk factors for osteoarthritis of the hip.[1–3] Still, the mechanism of disease in which these two entities lead to osteoarthritis remains unknown. While the bony morphology associated with these disease processes has been extensively studied,[4] less research has addressed the structure of the soft tissues surrounding the hip joint. Previous work has explored hip abductor size and structure in patients with DDH and osteoarthritis,[5–7] showing smaller abductor size in affected patients compared to controls, and additional work on women with chronic hip joint pain has found increased hip abductor size but decreased strength compared to controls.[8] Few studies have explored the hip abductors in younger, prearthritic and presurgery patients with FAI and DDH,[9,10] and these found mixed results however sample sizes were limited and full cross-sectional area or volume measurements were not performed. While this prior work suggests that hip osteoarthritis in the setting of DDH is associated with decreased abductor size, the main driver of this association is unclear, as it may be primarily due to effects of osteoarthritis such as inflammation and decreased mobility, or may instead be mainly driven by altered hip joint mechanics. This study compared hip abductor size in patients with prearthritic DDH and FAI to explore the association between prearthritic hip disease and hip abductor size while also assessing the role of altered hip joint mechanics.

DDH involves deficient coverage of the femoral head by the acetabulum, leading to increased load on the cartilage surrounding the hip joint.[11] This altered anatomy has also been associated with shortened hip abductor muscle moment arms and larger abductor muscle forces.[12] As a result, volume of the hip abductor muscles may be affected in this population. While studies on abductor size in DDH have shown mixed results,[8–10] previous work has shown that isometric hip muscle strength in patients with DDH undergoing periacetabular osteotomy was 13%–34% lower than the strength of the healthy volunteers both pre- and postsurgery.[13] This condition has also been associated with muscle and tendon pain, which negatively correlates with hip muscle strength.[14] Another muscle of interest in DDH is the iliocapsularis, which overlies the anteromedial hip capsule and is thought to hypertrophy to tighten the hip capsule and stabilize the femoral head.[15] Prior work comparing DDH (undercoverage) and FAI Pincer type (overcoverage) found significantly larger cross-sectional area of the iliocapsularis in DDH,[16] and a follow-up study on these patients found that the iliocapsularis-to-rectus femoris ratio for cross-sectional area, thickness, width, and circumference was significantly larger in DDH.[17]

On the other hand, FAI involves the abutment of the femoral head–neck junction and the acetabular rim due to morphological abnormalities. Cam-type FAI involves an abnormal femoral head–neck junction, and Pincer-type FAI involves excessive acetabular coverage of the femoral head.[18] Previous work by Casartelli et al. has shown that patients with symptomatic FAI demonstrate less isometric maximal torque, assessed by hand dynamometry, compared to healthy controls in adduction, flexion, external rotation and abduction,[19] and Nepple et al. showed that strength deficits of the affected side compared to the unaffected side were seen in 46% of patients for abduction and 42% for flexion.[20] While DDH and FAI can both eventually reach common endpoints of hip pain, decreased hip strength and osteoarthritis, the mechanisms of these two diseases are distinct, and thus we hypothesized that in prearthritic patients, hip abductor size would significantly differ between DDH and FAI groups. By clarifying these differences, we aim to better understand the mechanisms of each disease and how targeted muscle strengthening may be beneficial in each.

In addition to muscle volume, the proportion of noncontractile tissue in each muscle may also be affected; this phenomenon is commonly referred to as fatty infiltration. The accumulation of adipocytes in muscle has been linked to muscle disuse and dysfunction,[21] and is associated with decreased muscle strength.[22,23] As a result, this phenomenon is important to measure to understand whether increased muscle size primarily involves an increase in contractile or noncontractile muscle. For example, previous studies have found that the iliocapsularis demonstrated less fatty infiltration in patients with DDH compared to those with FAI,[16] and research on patients with hip osteoarthritis showed increased proportions of noncontractile tissue in the gluteal muscles compared to healthy controls.[5]

This study aimed to test the hypothesis that the gluteus medius, gluteus minimus and iliocapsularis muscles would be larger in patients with DDH, relative to matched patients with FAI. Specifically, this study aimed to assess differences in cross-sectional area of muscles in these groups for (1) overall muscle and (2) contractile versus noncontractile tissue.

2 | METHODS

This study received approval from the Institutional Review Board. This is a retrospective cohort study, level III. A cohort was formed of patients with prearthritic hip disease aged 18–40 years, with a clinical diagnosis of DDH or FAI between January 1, 2015 and December 31, 2019, who received magnetic resonance imaging (MRI) before hip surgery (Figure 1). Patients were excluded based on a history of previous ipsilateral hip surgery, a known hip disorder other than dysplasia (Legg–Calve–Perthes, slipped capital femoral epiphysis, chondrolysis) or a muscular disorder (Charcot–Marie–Tooth, muscular dystrophy, cerebral palsy, Ehlers–Danlos). Patients were also excluded if they had osteoarthritis of the hip, defined as Tönnis grade 2 or above. Allocation to DDH or FAI was based on conventional anteroposterior pelvis radiograph and clinical diagnosis. Clinical diagnosis was determined by each treating orthopedic surgeon (C. P. G, J. C. C) using the minimum criteria of groin and/or lateral hip pain for a period more than 3 months and radiographic findings. For this study, the DDH group was defined as having a lateral center edge angle (LCEA) ≤ 18°. The FAI group was defined as patients with

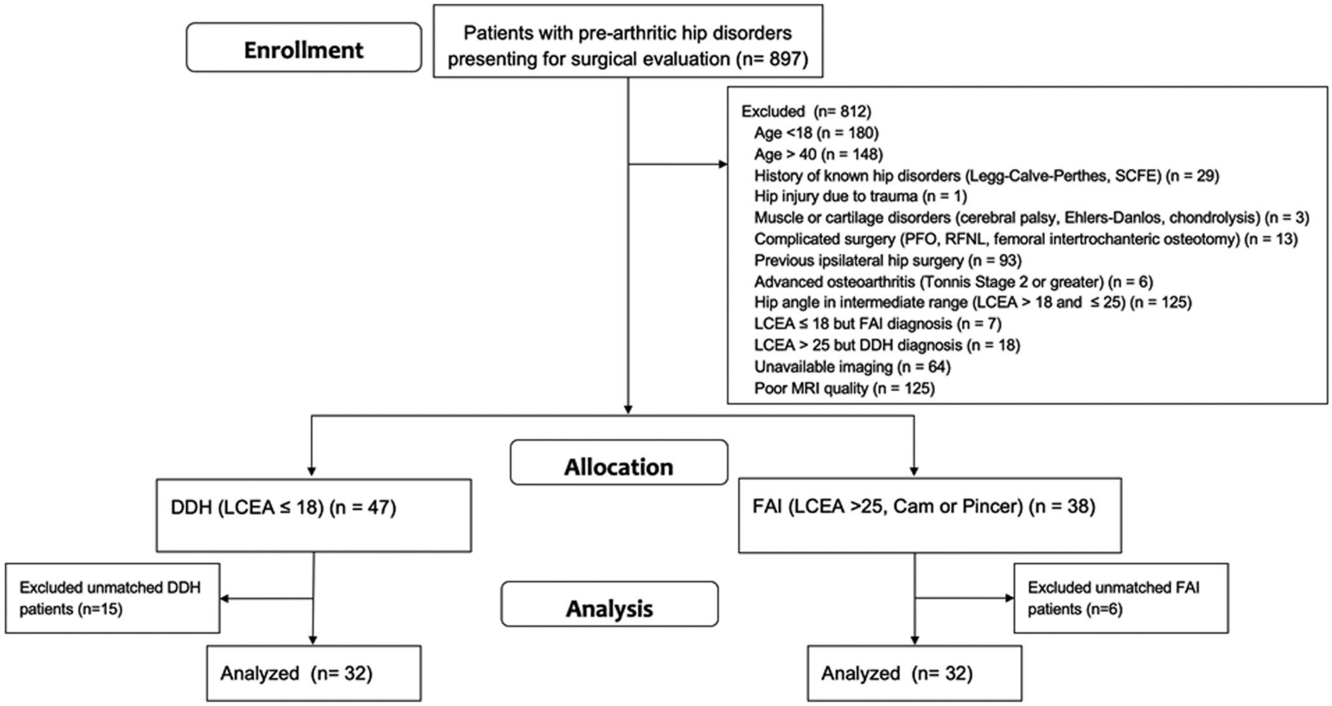

FIGURE 1 Study cohort selection criteria

Cam, Pincer, or Mixed FAI, for which the diagnosis of Cam-type FAI required an α angle ≥55°,[24] while Pincer-type FAI required an LCEA ≥ 40°.[25] All patients in the FAI group were also required to have an LCEA > 25° to draw a clear distinction from the DDH group. Patients with DDH were 1:1 matched to patients with FAI based on age (±5 years), sex, and body mass index (BMI) (±5 kg/m^2). Patients who lacked suitable matches based on these criteria were excluded; this included 15 patients with DDH and six patients with FAI.

In all patients, MR arthrography for the affected hip was performed. MR arthrography was chosen as the imaging modality, as it been shown to have superior resolution for observing the surrounding soft tissue.[26,27] Following careful training by two senior raters in the Orthopedic Surgery and Physical Therapy departments, two full sets of muscle measurements were performed by two medical students. To ensure the reproducibility and reliability of all study outcome measurements, two separate raters made complete sets of independent measurements, to assess interobserver variability. Each rater then made a second set of measurements for all images, spaced at least 1 week apart from the first, to assess intraobserver variability. Muscle size and composition were measured by observing the muscle cross-sectional area and the proportion of noncontractile tissue for the gluteus medius/minimus complex and iliocapsularis, using Amira software (Thermo Fisher Scientific). Specifically, the gluteus medius/minimus complex was measured in the transverse plane at both the anterior inferior iliac spine (AIIS) and the center of the femoral head, modified from an approach previously reported by Harris et al.[28] The iliocapsularis was measured by only one transverse slice at the center of the femoral head, due to its small size. Given that this muscle attaches at the AIIS, we felt the AIIS location did not represent this muscle adequately (Figure 2). After each muscle was outlined, the Local Thresholding module in the Amira software was applied, which detects local differences in intensity of the MRI to differentiate between muscle and noncontractile tissue. The program was then used to quantify the amount of each material within each circumscribed muscle (Figure 3).

Finally, potential effect modifiers in the association between DDH and muscle volume or composition were recorded, including activity level and pain duration. Activity level was measured by the University of California, Los Angeles activity score, which is a 10-point activity scale that evaluates patient activity ranging from fully inactive and dependent (level 1) to regular participation in impact sports such as jogging or tennis (level 10). This activity score may act as an effect modifier in this study, as inactivity can lead to muscle atrophy[29,30] and likewise exercise can lead to hypertrophy.[31] Additionally, as chronic hip pain has been associated with decreased abductor strength and volume,[8] patients were surveyed on the duration of their hip pain, with categories including less than 6 months, 6 months to 1 year, 1–3, 3–5 years, and greater than 5 years.

2.1 | Statistics

In estimating the sample size needed for this study, the iliocapsularis muscle was chosen as the determinant, because detecting changes in this small muscle required the largest sample size. The sample size was estimated based on the calculation reported by Babst et al. (2011),[16] who similarly compared iliocapsularis cross-sectional area between those with DDH and FAI. This paper assumed a mean

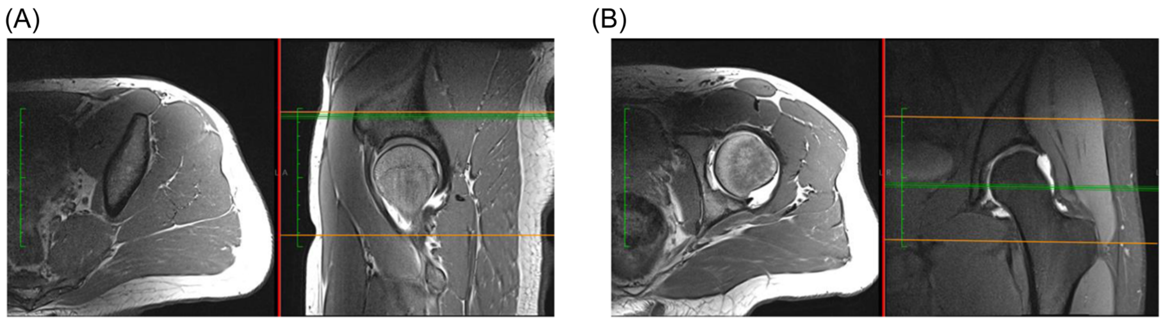

FIGURE 2 Magnetic resonance imaging landmarks used for muscle segmentation and noncontractile tissue measurement. (A) An example of the transverse slice selected for the anterior inferior iliac spine (left), and the corresponding sagittal view (right) used for slice identification. (B) The transverse slice selected for the center of the femoral head (left), identified by selecting the transverse slice with the widest circumference and by using the corresponding coronal view (right). In the sagittal and coronal images, the yellow lines indicate the upper and lower vertical boundaries of the corresponding transverse image series, and the green lines indicate the location of the transverse slice shown. [Color figure can be viewed at wileyonlinelibrary.com]

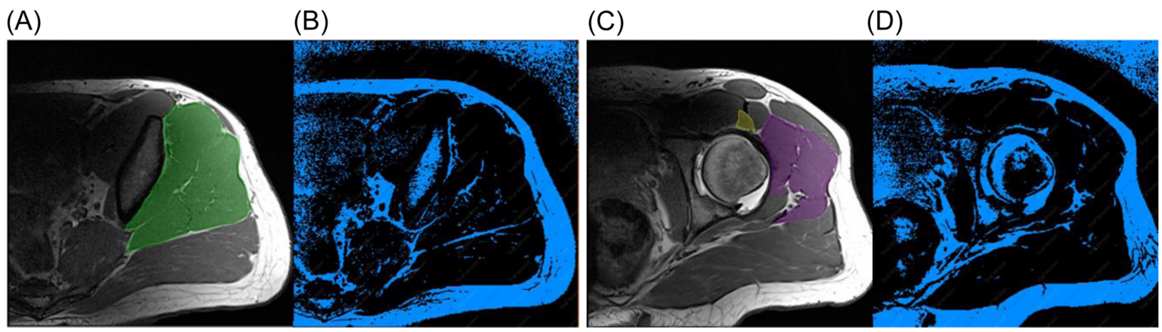

FIGURE 3 Magnetic resonance imaging cross-sectional area measurements and noncontractile tissue differentiation for the gluteus medius/minimus complex and iliocapsularis muscles. (A) Cross-sectional area measurement of the gluteus medius/minimus complex (in green) at the anterior inferior iliac spine (AIIS). (B) This AIIS slice after undergoing Local Thresholding transformation in the Amira software to differentiate between muscle and noncontractile tissue. (C) Cross-sectional area measurements at the femoral head of the gluteus medius/minimus complex (in purple) and the iliocapsularis (in yellow). (D) This femoral head slice after undergoing Local Thresholding transformation. [Color figure can be viewed at wileyonlinelibrary.com]

normal muscle width of 2.15 cm, a 20% muscular hypertrophy[32] and an estimated standard deviation (SD) of 0.5 cm. Using these values, along with a two-tailed α level of 0.05 and beta of 0.1, the sample size calculations for the current study resulted in a sample size estimation of 30 patients in each group. For patient characteristics (Table 1), numeric variables were compared using independent samples *t*-tests. Categorical variables with two categories were compared using Fisher's exact test, and categorical variables with more than two categories were compared using Pearson's χ^2 test. Differences in muscle size and composition were compared using paired samples *t*-tests, using a significance level of $p < 0.05$. Due to our 1:1 matching of patients based on age, sex, and BMI, we chose to use paired *t*-tests rather than unpaired *t*-tests for this comparison.[33,34] All values were presented as mean ± (SD). Standard error of measurement (SEM) ($\text{SEM} = \text{SD} \times \sqrt{1 - \text{ICC}}$) and the minimal detectable change (MDC) ($\text{MDC} = \text{SEM} \times 1.96 \times \sqrt{2}$) for each measurement technique were also calculated. Briefly, the SEM reflects absolute measurement error (response stability), and the MDC provides an objective threshold that can be used to determine whether values obtained are beyond measurement variability (i.e., smallest difference that can be accurately measured).[35,36] Intrarater and interrater reliability was calculated for all study measurements using the intraclass correlation coefficient (Table 2).

3 | RESULTS

The longitudinal cohort included 32 matched pairs. There were a total of 64 hips and 62 patients (2 patients had bilateral hip involvement). Due to matching criteria, there were no differences between groups in age, sex, or BMI (Table 1). Patients with DDH had significantly larger cross-sectional area of the gluteus medius/minimus muscle complex at both the AIIS and the femoral head (Figure 4, Table 3). The mean difference in overall muscle cross-sectional area at the AIIS was $4.07 \pm 7.4\ \text{cm}^2$ (12.1%), $p = 0.005$, and at the femoral head was $2.40 \pm 4.37\ \text{cm}^2$ (20.2%), $p = 0.004$. Over half of the matched pairs displayed a between-pair difference of >10% at the AIIS (54.8%) and femoral head (56.3%). When comparing contractile muscle only

TABLE 1 Demographic and radiographic patient characteristics

Parameter	DDH	FAI	*p* Value
Hips (number)	32	32	-
Age (years)	28.0 ± 6.4	28.6 ± 6.5	0.699
Sex (% male)	31.3%	31.3%	1.000
Right hips (%)	50.0%	53.1%	1.000
Weight (kg)	76.7 ± 13.7	74.4 ± 12.8	0.483
Height (cm)	170.8 ± 8.5	170.1 ± 10.9	0.784
BMI (kg/m^2)	26.2 ± 3.9	25.8 ± 4.2	0.660
LCE angle (°)	9.6 ± 7.0	31.1 ± 5.8	<0.001
Acetabular inclination (Tönnis angle in °)	17.9 ± 6.0	2.9 ± 3.7	<0.001
UCLA activity level (past 6 months, 1–10)			0.416
Low to moderate activity level (1–8)	60.0%	71.4%	
High activity level (9–10)	40.0%	28.6%	
Pain duration			0.213
Less than 6 months	9.4%	0.0%	
6 months to 1 year	9.4%	21.9%	
1–3 years	43.8%	53.1%	
3–5 years	15.6%	12.5%	
Greater than 5 years	21.9%	12.5%	

Note: For numeric patient characteristics, outcomes are presented as means with standard deviations. Categorical values are presented as percentages.

Abbreviations: BMI, body mass index; DDH, developmental dysplasia of the hip; FAI, femoroacetabular impingement; LCE, lateral center edge; UCLA, University of California, Los Angeles .

between the DDH and FAI groups, the DDH group again showed higher values. The mean difference at the AIIS was 4.46 ± 7.06 cm^2 (14.2%), $p = 0.001$, and at the femoral head was 2.88 ± 3.94 cm^2 (25.4%), $p < 0.001$. Over half of the matched pairs displayed a between-pair difference of >10% at the AIIS (56.3%) and femoral head (62.5%). Comparison of gluteal size to normative values is difficult, as few prior studies included control patients, and these mainly used muscle volume instead of cross-sectional area as an outcome measure.[37,38] There was no between-group difference in the proportion of noncontractile tissue in the gluteus medius/minimus complex; at the AIIS, the mean difference was −0.01 ± 0.06 cm^2 (−0.5%), $p = 0.119$, and at the femoral head this was −0.03 ± 0.11 cm^2 (7.3%), $p = 0.099$. The proportions of noncontractile tissue measured at the femoral head and AIIS were similar to prior studies in healthy patients. The present study found that the DDH group had an average proportion of noncontractile tissue in the gluteus medius/minimus complex of 7 ± 4% at the AIIS and 7 ± 1% at the femoral head, while the FAI group had averages of 8± 4% at the AIIS and 9 ± 8% at the femoral head. Recent work in a healthy

TABLE 2 Reliability and reproducibility of outcome measurements

Parameter	Muscle	Location	ICC intraobserver 1 (95% CI)	SEM intraobserver 1	ICC intraobserver 2 (95% CI)	SEM intraobserver 2	ICC interobserver (95% CI)
Muscle only, CSA (cm^2)	Gluteus med/min	AIIS	0.97 (0.96–0.99)	1.18	0.96 (0.93–0.98)	1.50	0.94 (0.91–0.96)
Muscle and noncontractile tissue, CSA (cm^2)	Gluteus med/min	AIIS	0.97 (0.95–0.98)	1.30	0.96 (0.94–0.98)	1.63	0.95 (0.91–0.97)
Proportion of noncontractile tissue	Gluteus med/min	AIIS	0.99 (0.98–0.99)	0.00	0.99 (0.98–0.99)	0.01	0.97 (0.95–0.98)
Muscle only, CSA (cm^2)	Gluteus med/min	FH	0.98 (0.96–0.99)	0.57	0.97 (0.94–0.98)	0.68	0.95 (0.93–0.97)
Muscle and noncontractile tissue, CSA (cm^2)	Gluteus med/min	FH	0.97 (0.94–0.99)	0.71	0.94 (0.91–0.97)	0.93	0.94 (0.91–0.97)
Proportion of noncontractile tissue	Gluteus med/min	FH	0.98 (0.97–0.99)	0.01	0.97 (0.95–0.98)	0.01	0.97 (0.95–0.98)
Muscle only, CSA (cm^2)	Iliocapsularis	FH	0.84 (0.74–0.9)	0.25	0.78 (0.66–0.87)	0.28	0.84 (0.75–0.89)
Muscle and noncontractile tissue, CSA (cm^2)	Iliocapsularis	FH	0.8 (0.68–0.88)	0.29	0.78 (0.64–0.86)	0.28	0.84 (0.74–0.91)
Proportion of noncontractile tissue	Iliocapsularis	FH	0.95 (0.91–0.97)	0.03	0.96 (0.93–0.98)	0.03	0.96 (0.93–0.98)

Abbreviations: AIIS, anterior inferior iliac spine; CSA, cross-sectional area; FH, femoral head; Gluteus med/min, gluteus medius/minimus complex; ICC, intraclass correlation coefficient; SEM, standard error of measurement.

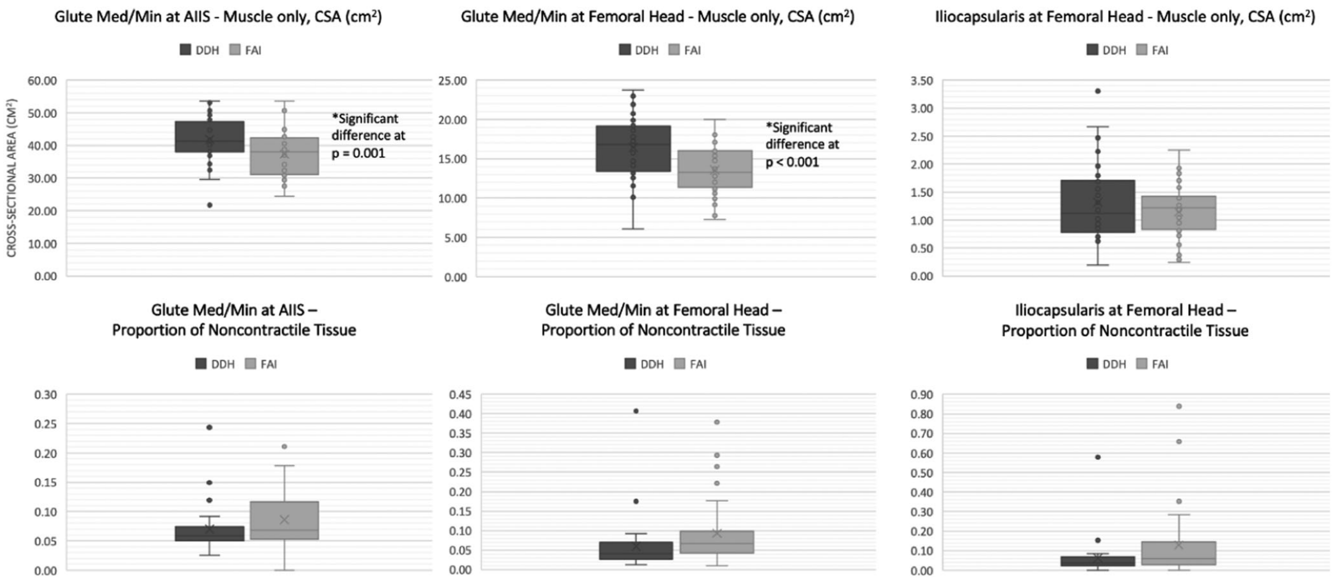

FIGURE 4 Muscle cross-sectional area (CSA) was measured for the gluteus medius/minimus complex, at both the anterior inferior iliac spine (AIIS) and the femoral head. This measurement was also performed for the iliocapsularis muscle at the femoral head. Muscle measurements were performed for the entire cross-sectional area, and were also separated by muscle and noncontractile tissue, as shown above. The top row of boxplots indicates cross-sectional area measurements of muscle only, and the bottom row indicates noncontractile tissue as a fraction of the entire cross-sectional area of each muscle. The CSA findings for the gluteus medius/minimus complex muscle components were significantly larger for the developmental dysplasia of the hip (DDH) group compared to the femoroacetabular impingement (FAI) group when measured at both transverse planes. In contrast, the proportion of noncontractile tissue did not differ between the groups. Together, these findings indicate larger abductor muscles in patients with DDH compared to those with FAI.

population has shown that a similar measurement termed "fat-signal fraction" has an overall average of 8.13 ± 1.70% at the gluteus medius and 9.89 ± 2.72% at the gluteus minimus. This prior study found a range in fat-signal fraction of 5.09%–13.41% at the gluteus medius and 5.69%–22.78% at the gluteus minimus, suggesting our findings are within the normal range.[38] There was also no difference in muscle cross-sectional area or proportion of noncontractile tissue in the iliocapsularis; when comparing overall muscle cross-sectional area, the mean difference was 0.18 cm^2 ($p = 0.195$), and when comparing contractile muscle only, the mean difference was 0.17 cm^2 ($p = 0.249$).

4 | DISCUSSION

This study aimed to explore how hip abductor muscles differ in DDH and FAI to better understand each mechanism of disease and to improve the future efficacy of treatments. Patients with DDH demonstrated a larger cross-sectional area of the gluteus medius/minimus muscle complex compared to those with FAI. Importantly, there were no group differences in the proportion of noncontractile tissue. This greater cross-sectional area of the gluteus medius/minimus muscle complex in patients with DDH, without the presence of greater noncontractile tissue, indicates a relatively larger amount of healthy muscle tissue in DDH compared to FAI. The study additionally assessed differences in the size and proportion of noncontractile tissue of the iliocapsularis muscle, and differences did not reach statistical significance.

One previous study by Le Bouthillier et al. investigated differences in hip abductor volume in three groups of patients: those with DDH, isolated labral tears, and CAM-type FAI.[10] Contrary to the present study, the Le Bouthillier study did not find a difference in gluteus medius and gluteus minimus volumes, and this difference in findings may be explained by differing methodologies. Le Bouthillier et al. defined DDH using the commonly accepted definition of LCEA of <20°,[39] however the present study defined DDH by LCEA ≤ 18° to draw a clear contrast between patients with and without dysplasia. Additionally, Le Bouthillier et al. did not clearly indicate that other hip and muscular diseases were excluded, such as Legg–Calve-Perthes, slipped capital femoral epiphysis, muscular dystrophy, or cerebral palsy, nor did they control for confounding factors, such as age, sex, and BMI. Finally, the sample size of the Le Bouthillier study was smaller with 17 patients, and that study only assessed muscle size by measuring a single distance, defined as the short-axis thickness of the gluteal muscles at a transverse MRI slice,[10] in contrast with the cross-sectional area measurement of our study.

Another recent study by Chalian et al. used computed tomography (CT) to investigate gluteal muscle area, circumference and muscle density among prearthritic patients with DDH, FAI, and asymptomatic healthy patients.[9] Muscle density was not clearly defined, however no differences were found among the three groups, and no differences in gluteal area or circumference were found between

TABLE 3 CSA and noncontractile tissue infiltration of gluteus medius/minimus complex and iliocapsularis

Parameter	Muscle	Location	DDH	FAI	Paired differences, DDH vs. FAI	Minimal detectable change	Average percent difference	Percent of pairs with difference >10%	*p* Value (paired samples *t*-test)
Muscle only CSA (cm^2)	Gluteus med/min	AIIS	41.80 ± 7.13	37.34 ± 6.83	4.46 ± 7.06	3.27	14.2%	56.3%	**0.001**
Muscle and noncontractile tissue, CSA (cm^2)	Gluteus med/min	AIIS	44.93 ± 7.51	40.93 ± 8.13	4.07 ± 7.4	3.60	12.1%	54.8%	**0.005**
Proportion of noncontractile tissue	Gluteus med/min	AIIS	0.07 ± 0.04	0.08 ± 0.04	−0.01 ± 0.06	0.01	−0.5%	35.5%	0.119
Muscle only CSA (cm^2)	Gluteus med/min	FH	16.45 ± 4.07	13.57 ± 3.13	2.88 ± 3.94	1.58	25.4%	62.5%	**<0.001**
Muscle and noncontractile tissue, CSA (cm^2)	Gluteus med/min	FH	17.40 ± 3.93	15.00 ± 3.3	2.40 ± 4.37	1.97	20.2%	56.3%	**0.004**
Proportion of noncontractile tissue	Gluteus med/min	FH	0.05 ± 0.07	0.09 ± 0.08	−0.03 ± 0.11	0.03	7.3%	21.9%	0.099
Muscle only CSA (cm^2)	Iliocapsularis	FH	1.32 ± 0.68	1.14 ± 0.48	0.17 ± 0.84	0.69	64.2%	50.0%	0.249
Muscle and noncontractile tissue, CSA (cm^2)	Iliocapsularis	FH	1.46 ± 0.68	1.3 ± 0.48	0.18 ± 0.69	0.80	23.8%	50.0%	0.195
Proportion of noncontractile tissue	Iliocapsularis	FH	0.07 ± 0.1	0.13 ± 0.18	−0.07 ± 0.24	0.08	184.8%	25.0%	0.117

Note: Groups were compared using paired samples *t*-tests. Percent difference was calculated as (DDH value − FAI value)/FAI value for each pair. This was then averaged across all pairs to get average percent difference. Bold values indicate findings that reach statistical significance, defined as $p < 0.05$.

Abbreviations: AIIS, anterior inferior iliac spine; CSA, cross-sectional area; DDH, developmental dysplasia of the hip; FAI, femoroacetabular impingement; FH, femoral head; gluteus med/min, Gluteus medius/minimus complex.

patients with DDH and controls or between the affected sides of patients with DDH and FAI. Chalian et al. measured muscle cross-sectional area just below the sacroiliac joint, in contrast to the AIIS and femoral head, so their findings were not directly comparable to ours. Other differences between the Chalian study and ours include their use of the TeraRecon software, a smaller sample size of 16 patients with DDH, and the use of CT rather than MRI imaging to perform muscle measurements. The use of MRI in our study may be a strength, as MRI has been shown to have better visualization than CT for observing soft tissue.[26,27]

Prior studies have also investigated abductor size in patients with hip osteoarthritis, and found decreased hip abductor size on the affected side compared to the control.[5-7] Zacharias et al. found that patients with unilateral osteoarthritis had less gluteal muscle volume and greater levels of noncontractile tissue based on the Goutallier criteria compared to both the patients' contralateral side and people without hip osteoarthritis, and gluteal atrophy had a positive correlation with clinical osteoarthritis severity.[5,6] Liu et al. similarly found that in patients with DDH and osteoarthritis undergoing total hip arthroplasty, cross-sectional area and radiological density of the gluteus medius were smaller on the dysplastic side compared to the unaffected side.[7] The contrast between these findings in the osteoarthritis population and the present findings of relatively larger ipsilateral hip abductors in the prearthritic population of patients with DDH compared to those with FAI raises the possibility that the hip abductors may first hypertrophy in patients with DDH to compensate for hip instability, and then atrophy may occur as osteoarthritis progresses. In osteoarthritis, changes in the musculature surrounding the hip joint may be related to both biomechanical changes and other systemic metabolic changes involved in the disease,[40] while in prearthritic DDH and FAI, these muscular changes may be more directly related to biomechanics due to the abnormalities in bone shape and joint loading.[1] Compensatory muscle changes in prearthritic hip disorders may improve hip stability, however they also may increase stress within the joint,[12] and further research is needed so that healthy muscle function may be maintained.

By comparing patients with symptomatic DDH to those with symptomatic FAI, one key question the present study addresses is whether changes in hip stabilizer muscles are driven by hip pain or by mechanical effects of the hip pathology. Prior work has studied hip abductor strength and volume in patients with chronic hip joint pain (CHJP), associated with labral tears, femoroacetabular impingement, chondral lesions, and structural instability.[8,41] This previous research has shown that patients with CHJP demonstrate less hip abductor strength[8,41] and greater hip abductor volume[8] compared to those without CHJP, with potential explanations including increased noncontractile tissue volume and muscle hypertrophy. Our finding of a significantly different abductor size in patients with DDH and FAI despite similar activity and pain levels (Table 1) suggests that muscle changes are less likely to be driven by pain, and more likely to be explained by mechanical differences in these hip pathologies. Further research is needed to confirm our speculation.

Given that the present study did not have a control group without pain or abnormal bony morphology, we cannot say that hip abductor muscles in DDH are hypertrophied or those in FAI are atrophied relative to normal. However, previous studies on the mechanics of DDH may suggest that hypertrophy in DDH is occuring. Recent studies have confirmed that biomechanical differences in DDH include a smaller lateral center edge angle ($10.8 \pm 9.1°$ vs. $27.3 \pm 4.3°$, $p < 0.001$),[28] larger neck shaft angle ($138.4 \pm 4.8°$ vs. $131.7 \pm 5.8°$, $p = 0.001$),[28] and a lateralized hip joint center leading to higher medially-directed joint reaction forces.[28,42] Additionally, patients with DDH have shorter muscle moment arm lengths for the primary hip abductors and larger abductor muscle forces throughout stance compared to healthy controls.[12] The abductors are thought to have a mechanical disadvantage due to the shortened moment arm, and must produce increased internal force to adequately stabilize the hip. A recent study by Harris et al. supports this hypothesis with the finding that gluteus medius size was significantly larger in patients with DDH compared to asymptomatic patients without DDH, and no differences in noncontractile tissue volume were found.[28]

In addressing the second component of the present study's question regarding differences in the iliocapsularis muscle, we did not find any difference between groups. While the gluteal hypertrophy in patients with DDH has been suggested to be due to a shorter moment arm as described above, the iliocapsularis is instead thought to hypertrophy to tighten the anterior hip capsule and stabilize the femoral head.[15] This stabilizing role makes sense given its position overlying the anteromedial hip capsule, and this role may be particularly helpful during full extension and external rotation when the iliocapsularis muscle is maximally stretched.[16,17] One study by Babst et al. comparing DDH and FAI found significant differences in both the cross-sectional area and fatty infiltration of the iliocapsularis,[16] and a follow-up study on similar patients found that the iliocapsularis-to-rectus femoris ratio for cross-sectional area, thickness, width, and circumference was significantly larger for the DDH group.[17] Our differing results may be explained by the fact that our FAI cohort consisted of patients with Cam, Pincer, or Mixed FAI, and required an LCEA > 25°. In contrast, the Babst et al. authors defined their FAI cohort as an LCEA > 39°, which is the definition of Pincer-type FAI according to Tönnis and Heinecke.[43] As a result, the present study compares patients with DDH to a wider selection of patients with FAI, rather than only those Pincer-type FAI. Additionally, the present study used the center of the femoral head as the sole landmark to measure the iliocapsularis, while both Babst et al. and Ward et al. measured slightly lower at 4 cm below the AIIS,[15,16] and Babst et al. also measured at the first slice below the femoral head.[16] Future studies may want to pursue full volume measurements of this muscle to confirm our findings.

5 | LIMITATIONS

This study had a number of limitations. First, the patient population was limited to those who were symptomatic and sought care for hip conditions at a tertiary care center, which may attract particularly unique and challenging cases. This study attempted to correct for this by excluding patients who had more complex disorders, such as Legg–Calve–Perthes disease and slipped capital femoral epiphysis. Second, our longitudinal patient database consisted of patients with symptomatic hips presenting for a surgical consult, therefore we did not include a true control group. For this reason, we cannot say that patients with DDH demonstrate hypertrophied abductor muscles relative to normal.

6 | FUTURE DIRECTIONS

Future studies using asymptomatic patients without DDH or FAI will be necessary to confirm whether abductor compensation for altered hip joint mechanics in DDH is occurring, and to elucidate the mechanism of this potential muscle compensation, with the goal of improving interventions to optimize muscle function in these patients. Exploring abductor size in patients with early versus late DDH and mild versus severe DDH could also be helpful in understanding the role of the abductors as progression to osteoarthritis occurs.

7 | CONCLUSION

In conclusion, dysplastic hips demonstrated a larger cross-sectional area of the gluteus medius/minimus muscle complex compared to hips with femoroacetabular impingement. This increased muscle was not associated with greater noncontractile tissue, indicating healthy muscle tissue. This finding may be explained by the mechanical disadvantage and increased force requirement of the abductor muscles in hip dysplasia.

AUTHOR CONTRIBUTIONS

Emma R. Payne and Cecilia Pascual-Garrido conceived of the research idea. Emma R. Payne, Michael D. Harris, and Cecilia Pascual-Garrido designed the study. Michael D. Harris and Cecilia Pascual-Garrido instructed Emma R. Payne and Chadi Nahal on measurement approaches for data acquisition. Emma R. Payne and Tomoyuki Kamenaga performed the data analysis. Emma R. Payne took the lead in writing the manuscript with input from Marcie Harris-Hayes, Cecilia Pascual-Garrido, Michael D. Harris, and John C. Clohisy. All authors have read and approved the final submitted manuscript.

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CONFLICTS OF INTEREST

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