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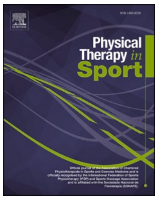

Original Research

The association between lateral hip muscle size/intramuscular fat infiltration and hip strength in active young adults with long standing hip/groin pain

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ABSTRACT

Objectives: To investigate associations between lateral hip muscle size/intramuscular fat infiltration (MFI) and hip strength in active young adults with longstanding hip/groin pain.
Design: Cross-sectional study.
Setting: University/Clinical.
Participants: Sub-elite soccer and Australian Football players (n = 180; 37 female) with long standing hip/groin pain.
Main outcome measures: Muscle size (volume) and MFI of gluteus maximus, medius, and minimis, and tensor fascia latae (TFL) were assessed using magnetic resonance imaging. Isometric hip strength was measured with handheld dynamometry. Associations between muscle size/MFI were assessed using linear regression models, adjusted for body mass index and age, with sex-specific interactions.
Results: Positive associations were identified between lateral hip muscle volume and hip muscle strength, particularly for gluteus maximus and gluteus minimus volume. For all muscles, hip abduction was associated with an increase in strength by up to 0.69 N (R^2 ranging from 0.29 to 0.39). These relationships were consistent across sexes with no sex interactions observed. No associations were found between MFI and strength measures.
Conclusion: Greater lateral hip muscle volumes are associated with greater hip strength in active young adults with long standing hip/groin pain, irrespective of sex. Gluteus maximus and minimus volume showed the most consistent relationships with hip strength across multiple directions.

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1. Background

Hip and groin pain (hip/groin pain) is a common complaint among young adults who participate in sports involving kicking and frequent changes of direction (Mosler et al., 2018; Waldén, Hägglund, & Ekstrand, 2015). Hip/groin pain can impact health and performance and is often associated with re-injury, reduced quality of life, and development of chronic pain (Mosler et al., 2018; Roughead et al., 2022; Whalan, Lovell, McCunn, & Sampson, 2019). Individuals with hip/groin pain commonly demonstrate weakness in their lateral hip muscles, which include the gluteal muscle group and tensor fascia latae(TFL) (Freke et al., 2016; Kemp et al., 2014; Retchford et al., 2018). These muscles play a crucial role in movement and hip joint stability during sport and everyday activities, particularly during single-leg stance (Al-Hayani, 2009; Gottschalk, Kourosh, & Leveau, 1989; Retchford, Crossley, Grimaldi, Kemp, & Cowan, 2013).

Individuals with hip/groin pain may have reduced hip muscle size (Lawrenson et al., 2019; Malloy et al., 2019) and greater amounts of fatty infiltrate within these muscles (Koch et al., 2021), indicating a loss of muscle quality. Intramuscular fat infiltration (MFI) refers to an accumulation of fat within a muscle, believed to reduce the availability of contractile, force-generating tissue leading to muscle weakness and reduced function (Addison, Marcus, LaStayo, & Ryan, 2014; Goodpaster et al., 2004). By combining assessments of muscle structure with strength tests, a more comprehensive understanding of overall muscle function can be achieved, allowing for the identification of individual muscle impairments. This integrated approach may facilitate the development of focused and targeted interventions, thereby enhancing the management of hip/groin pain.

The relationship of lateral hip muscle size and MFI with hip strength, in active young adults with hip/groin pain remains unclear. It is possible that diminished hip muscle function could potentially lead to hip/groin pain or exacerbate symptoms in these individuals. Moreover, active young adults with hip/groin pain may face an elevated risk of developing hip osteoarthritis (OA) compared to their healthy counterparts (Agricola et al., 2013; Petrillo, Papalia, Maffulli, Volpi, & Denaro, 2018; Vigdorchik, Nepple, Eftekhary, Leunig, & Clohisy, 2017). Studies have indicated a relationship between the severity of hip OA symptoms, reduced lateral hip muscle size, and higher levels of MFI(15, 22–24). Individuals with hip OA also tend to exhibit lower hip abductor strength when compared to healthy controls (Marshall, Noronha, Zacharias, Kapakoulakis, & Green, 2016). Understanding hip muscle characteristics before the onset of worsening hip joint changes is important to prevent or potentially delay the progression of degenerative changes and allow the development of effective management strategies.

The influence of sex on hip muscle characteristics and the experience of hip/groin pain warrants further investigation. Previous research has indicated notable differences between males and females in terms of lateral hip muscle mass distribution, fat composition, and lower limb biomechanics in the hip/groin pain (Belzunce, Henckel, Di Laura, Horga, & Hart, 2023; Douma, Casartelli, Sutter, Leunig, & Maffiuletti, 2023; King et al., 2019). These differences are likely to impact the strength and function of the lateral hip muscles, potentially influencing the presentation and management of hip/groin pain in young adults. Additionally, the susceptibility to certain musculoskeletal conditions, including hip osteoarthritis, has been observed to vary with sex, which could be related to underlying differences in muscle structure and function (Cowan et al., 2020; Maffiuletti et al., 2020; Marshall et al., 2016).

1.1. Aim

The aim of this study was to explore associations between lateral hip muscle size and MFI measured using magnetic resonance imaging (MRI) with hip muscle strength in active young adults experiencing long standing hip/groin pain and to examine the influence of sex on this relationship.

2. Methods

2.1. Study design

This cross-sectional study used baseline data from the Femoroacetabular Impingement and hip Osteoarthritis Cohort (FORCe) study (Crossley et al., 2017). The FORCe study is an ongoing prospective cohort study in sub-elite football (soccer and Australian football) players with hip/groin pain. Institutional ethics was approved (HEC15-019 and HEC16-045; 2015000916 and 2016001694) and written informed consent was obtained from all participants.

2.2. Sample size

This study is an exploratory secondary analysis of baseline data collected in a prospective cohort study (Crossley et al., 2017). Therefore no a *priori* sample size was established for this outcome.

2.3. Participants

The FORCe study recruited adults aged 18–50 years who regularly participated in either soccer or Australian Football (AF) and complained of hip/groin pain lasting more than 6 months (Crossley et al., 2017). Participants were recruited from the community via social and print media advertising or through information sessions conducted at soccer and AF clubs in Melbourne and Brisbane, Australia. The baseline recruitment period spanned from August 2015 to October 2018.

Participants were eligible for the study if they met the following criteria for self-reported hip/groin pain: 1) Gradual pain onset, 2) Duration of at least six months, and 3) Average hip/groin pain rated between three and eight on an 11-point numeric pain rating scale, during football or football-specific movements, and 4) Had a positive FADIR (Flexion, adduction, internal rotation) test (Shanmugaraj et al., 2020). Participants with a Kellgren and Lawrence grade of >1 (hip joint OA changes) (Heerey et al., 2021) were excluded (Supplementary 1).

2.4. Variables

Demographic information (e.g., age, height, body mass) for all participants was collected. Participants reported their most symptomatic hip on the International Hip Outcome Tool (iHOT-33) questionnaire, based on their response to the question “which (hip) gives you the most trouble?“, and this hip was used for analyses (Mohtadi et al., 2012). Complete data were analysed, missing data were not substituted.

2.5. Strength outcomes

Isometric hip strength was measured in six directions; abduction, adduction, flexion, extension, external rotation (ER), and internal rotation (IR) using a handheld dynamometer (Commander Muscle Tester; JTECH Medical Industries, Inc, Midvale, UT) via a ‘make test’ protocol (Crossley et al., 2017). Each participant was allowed a ‘practice trial’ for task familiarisation, followed by three maximal trials in each direction (Supplementary 2). The muscle contractions were held for 5 s each, with breaks of 5 s in between each trial. At least 30 s rest was included between testing each movement to minimise the effects of fatigue. The maximum force in Newtons (N) was recorded and used for analyses.

2.6. Magnetic resonance imaging and outcomes

Hip muscle size and MFI were assessed using MRI (3.0-T, Philips Ingenia, Netherlands, software version 4.1.3.2), following a standard protocol (Heerey et al., 2021). Bilateral hip and pelvic MRIs were performed in supine with a 32-channel torso placed over the hips and pelvis, collecting 216 axial slices. The field of view included the pelvis and hips from the iliac crest proximally, to just inferior to the lesser trochanter distally. Other acquisition parameters included: slice thickness, 1.5 mm; slice gap, 0 mm; repetition time, 3.5ms; echo time, TE1 1.2ms; Voxel, TE2 1.2 mm; bandwidth 0:38Hz. MRI images were reviewed and images with observable artifacts were removed from analysis.

The Dixon sequence uses water and fat images to quantify muscle volume and fat in various conditions including musculoskeletal pain, neurological and metabolic conditions, as well as in healthy aging populations (Belzunce, Henckel, Fotiadou, Di Laura, & Hart, 2020; Schlaeger et al., 2018). For this study, multipoint axial Dixon images were acquired. Images representing fat and water were converted to 3D Neuroimaging Informatics Technology Initiative (NIfTI) format and then exported to ITK-Snap software (Version 3.8.0; University of Pennsylvania, 2018) for analysis (Yushkevich et al., 2006).

An automated muscle segmentation process (Weber et al., 2019; Wesselink et al., 2022) was employed to trace each muscle boundary on every axial slice at the region of interest, starting at the superior iliac crest and extending to its distal insertion. For gluteus maximus, the majority of the muscle fibres (up to 80%) blend distally into the fascia latae at the level of the iliotibial band and into the lateral intermuscular septum, which are beyond the included field of view (Antonio, Wolfgang, Robert, Fullerton, & Carla, 2013; Reiman, Bolgla, & Loudon, 2012). To ensure consistency of size and intramuscular fat measures, gluteus maximus was anchored distally at the axial slice that best represents the most medial aspect of the lesser trochanter.

Following the tracing of muscle cross-sectional area on each slice, the resulting measurements were combined to generate a 3D mask for each muscle (Koch et al., 2021). The automated method utilised a water-only Dixon image to label the left and right hip abductor muscles (Wesselink et al., 2022). Automation segmentation algorithm was developed using 52 manually segmented Dixon scans (Stewart et al., 2023).

2.7. Muscle size

Although assessment of a single axial anatomical cross-sectional area is a faster alternative for estimating muscle size, it is not always representative of the muscle volume (Akagi et al., 2009). There is also no consensus on the optimal level for measurement, which limits its application (Perraton et al., 2022). Therefore, muscle volume measurement for the lateral hip muscles was chosen over cross-sectional area measurement, to ensure accurate representation of muscle size, Fig. 1. Volume (cm^3) measures were calculated by adding the CSA (cm^2) of each slice together and multiplying by slice thickness using the 'neurobase' R package (version 2022.2.2.485).

2.7.1. Intramuscular fat

To account for anatomical and electromyography studies that have identified distinct functional regions, the gluteus medius and minimus were divided into three (anterior, middle, posterior) and two (anterior, posterior) equal segments, respectively, for muscle fat calculations (Flack, Nicholson, & Woodley, 2014; Semciw et al., 2013, 2014). The 'neurobase' R package (version 1.32.3) performed all muscle fat calculations, with voxel intensity values extracted from the regions of interest in both fat and water-only images. Intramuscular fat was assessed using a muscle fat index (MFI), a metric that quantified the proportion and distribution of fat within individual muscles. The MFI was computed using the formula as previously described: MFI = fat/(fat + water) (Koch et al., 2021; Weber et al., 2019).

To assess intramuscular fat along the length of the muscle, normalisation of muscle length was conducted, where 0% represented the most proximal slice and 100% represented the most distal slice (Koch et al., 2021; Rostron et al., 2022). Mean MFI values were determined for each slice and were interpolated using spline interpolation to represent every 1% of muscle length. A descriptive analysis was performed to characterise the distribution of MFI along the length of each muscle and its respective segments.

2.8. Data analysis

Data were assessed for normality and linearity using box plots or scatterplots, in addition to Shapiro-Wilk tests and Q-Q plots. Demographic data were analysed for sex differences using Student t-tests for normally distributed data, or Mann-Whitney U tests for non-normally distributed data.

To investigate the cross sectional association between lateral hip muscle volume and isometric hip strength, linear regression models were employed. This decision was based on scatterplots and correlation coefficients that confirmed linear relationships and the distribution of residuals suggesting linearity. Age, body mass index (BMI), and sex were included as covariates in the model, as they are known to influence muscle strength (Brent, Myer, Ford, Paterno, & Hewett, 2013;

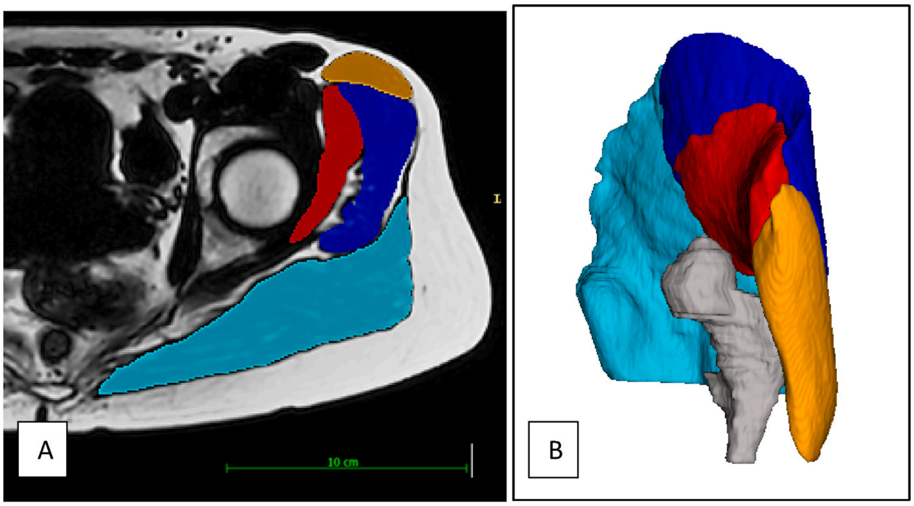

Fig. 1. Visualisation of the lateral muscles using MRI. **A:** Axial MRI slice of the left hip with color-coded tracings indicating individual muscles: Tensor fasciae latae (orange), Gluteus maximus (aqua), Gluteus medius (blue), and Gluteus minimus (red) **B:** Three-dimensional reconstruction derived from MRI data illustrating the volumetric distribution of lateral hip muscles, corresponding to the color coding in Panel A. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Nikolaidis, 2012). Regression coefficients with 95% confidence intervals were used to estimate the association between the independent variable (muscle volume) and dependent variable (isometric hip strength). To explore the potential effect modification of sex, we calculated interaction statistics (sex*volume). The coefficient of determination (R^2) was used to measure the variance in hip strength that could be explained by muscle volume. R^2 values range from 0 to 1, with higher values indicating a stronger relationship. To interpret R^2 values, Cohen's (1988) guidelines (Cohen, 1988) were followed, where R^2 values between 0.02 and 0.13 were considered weak, values between 0.13 and 0.26 were moderate, and values greater than 0.26 were considered substantial. Data were stratified by sex if significant interactions were detected.

All statistical analyses were performed using RS (version 2022.02.2 + 485) (Team, 2020), with a pre-specified α level of <0.05.

To investigate the association between MFI and muscle strength, statistical parametric mapping (SPM) methodology was used (Pataky, 2012). The SPM analysis generated a scalar output statistic, referred to as the 't' statistic, for the relationship between strength and muscle fat for each 1% increment along the muscle length. Regression analysis was performed within the SPM framework to identify the points along the length of the muscle that crossed a critical value (t), and thus identified a significant relationship between strength and MFI(16). The SPM1D (Statistical Parametric Mapping 1D) package, an open-source software (version 0.4) (spm1d.org), was used for this analysis and Python 3.9 (python.org) served as the programming language for implementing the analysis (Pataky, 2012). A significance threshold of $\alpha = 0.05$ was used for determining statistical significance.

3. Results

From 182 available participants (Heerey et al., 2021), a total of 180 participants (98.9%) were included in this study, comprising of 143 males and 37 females. Shapiro-Wilk tests indicated a deviation from normality in age, height, weight, BMI, and symptom duration ($p < 0.05$); therefore, Mann-Whitney U tests were used to assess differences between sexes. Average age did not differ between sexes, but men were significantly taller, heavier, had a greater BMI, and had longer duration of symptoms than women, Table 1.

3.1. *The relationship between muscle volume and hip strength*

No sex interactions were observed (Supplementary 3) therefore data were not stratified by sex. The adjusted model revealed moderate to strong associations between the volumes of all lateral hip muscles and the corresponding measures of muscle strength (Table 2, Supplementary 3). A substantial positive relationship was found between all lateral hip muscle volumes and hip abduction strength ($R^2 = 0.29$–0.39). For the individual muscles, every 1 cm^3 increase in volume had a relative increase in strength of 0.69 N for gluteus minimus, 0.10 N for gluteus maximus, 0.22 N for gluteus medius and 0.25 N for TFL. Other substantial relationships included hip adduction strength (gluteus minimus $R^2 = 0.29$, gluteus medius $R^2 = 0.26$), extension strength (gluteus maximus $R^2 = 0.26$), and external rotation strength (gluteus minimus $R^2 = 0.33$). Gluteus maximus and minimus were the two muscles that showed moderate to substantial relationships for all strength measures ($R^2 = 0.16$–0.39).

Table 1

Characteristics of participants.

n = 180	All	Male	Female	P value
Sex [n] (%)		143 (79.4)	37 (20.6)	
Age [years] (SD)	27.69 (±6.2)	27.72 (±6.3)	27.57 (±6.1)	0.726
Body mass [kg] (SD)	78.63 (±12.6)	82.04 (±10.7)	65.50 (±11.0)	<0.001*
Height [m] (SD)	1.78 (±0.1)	1.81 (±0.1)	1.67 (±0.1)	<0.001*
BMI [kg/m^2] (SD)	24.67 (±3.2)	25.01 (±3.1)	23.36 (±3.3)	<0.001*
Symptom duration [months] (IQR)	41 (34)	44 (44)	28 (25)	0.002*

Values are reported as means with standard deviations (SD), except for symptom duration, which is presented as the median and interquartile range (IQR). Statistical significance is denoted by $*p < 0.05$.

Table 2

Multivariable regression analysis: Association between lateral hip muscle volume and hip strength measures.

Peak strength	Muscle	Estimate [95% CI](**Newton**)	R^2	P value
Abduction	Gmin	0.69 [0.46 to 0.93]	0.39	<0.001*
	Gmax	0.10 [0.06 to 0.14]	0.35	<0.001*
	Gmed	0.22 [0.13 to 0.32]	0.35	<0.001*
	TFL	0.25 [0.01 to 0.50]	0.29	0.046*
Adduction	Gmin	0.57 [0.29 to 0.85]	0.29	<0.001*
	Gmed	0.17 [0.06 to 0.28]	0.26	0.003*
	Gmax	0.05 [0.00 to 0.10]	0.24	0.039*
	TFL	0.03 [-0.25 to 0.31]	0.22	0.837
Flexion	Gmax	0.13 [0.04 to 0.22]	0.18	0.007*
	Gmin	0.71 [0.17 to 1.25]	0.18	0.011*
	TFL	0.54 [0.01 to 1.06]	0.16	0.048*
	Gmed	0.14 [-0.08 to 0.35]	0.15	0.215
Extension	Gmax	0.26 [0.16 to 0.35]	0.26	<0.001*
	Gmin	1.27[0.71 to 1.84]	0.22	<0.001*
	Gmed	0.34 [0.11 to 0.57]	0.17	0.004*
	TFL	0.72 [0.16 to 1.29]	0.16	0.013*
External Rotation	Gmin	0.62 [0.41 to 0.83]	0.33	<0.001*
	Gmax	0.06 [0.02 to 0.10]	0.24	0.003*
	Gmed	0.13 [0.04 to 0.22]	0.24	0.005*
	TFL	0.16 [-0.06 to 0.38]	0.21	0.158
Internal Rotation	Gmin	0.44 [0.24 to 0.65]	0.21	<0.001*
	Gmed	0.13 [0.05 to 0.22]	0.18	0.002*
	Gmax	0.05 [0.01 to 0.08]	0.16	0.017*
	TFL	0.06 [-0.15 to 0.27]	0.14	0.585

Abbreviations: Gmax = Gluteus maximus, Gmed = Gluteus medius, Gmin = Gluteus minimus, TFL = Tensor fascia latae. Multivariable regression analysis includes age, BMI, and sex as covariates; ☐ significant substantial relationship, ☐ significant moderate relationship *Significance level at $p < 0.05$.

3.1.1. *The relationship between intramuscular fat and muscle strength*

The distribution of MFI was generally uniform across the lateral hip muscles. The gluteus medius and minimus anterior segments demonstrated greater MFI within the proximal third, as illustrated in Fig. 2E and C, respectively. Conversely, the gluteus minimus posterior and TFL segments displayed a smaller rise in MFI towards the distal third, with the TFL showing this increase across a broader mid-to-distal range, as evidenced by Fig. 2B and D. The statistical analysis conducted within the SPM framework revealed that there was no relationship between MFI and any of the strength measures across the entire muscle lengths (Supplementary 4).

4. Discussion

We aimed to explore associations between lateral hip muscle volume and MFI and hip muscle strength in active young adults with hip/groin pain. There was a positive relationship between lateral hip muscle volume and hip strength. Muscle volume had the strongest relationships with hip abduction strength, accounting for up to 39% in the variation of strength scores when adjusted for age, sex and BMI. These results indicate that individuals with larger lateral hip muscles may possess greater hip strength, even in the presence of long standing hip/groin pain. No sex interactions were found for the relationship between strength and muscle volume indicating that the relationship was consistent between males and females. A relationship was also not found between MFI and hip strength measures. This may imply that, within the context of our study population, MFI did not substantially impact hip strength. However, this observation warrants further investigation to fully understand

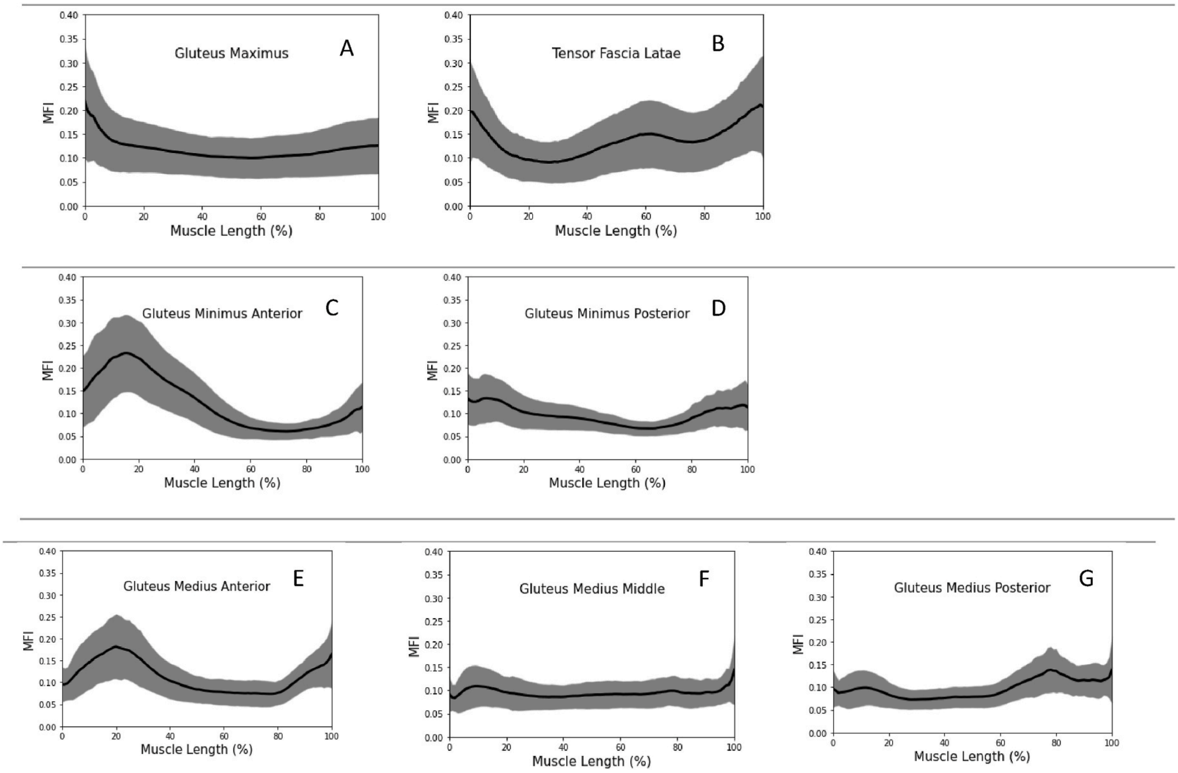

Fig. 2. Intramuscular fat infiltration along the length of muscle: A–G: Means and SD for proportion of intramuscular fat infiltration along the length of the muscle/ segments (0%–100% = proximal to distal).

the implications of MFI on muscle function and strength.

4.1. Lateal hip muscle volume

A recent systematic review has reinforced the relationship between muscle size and strength in the lower limbs, observed in a diverse populations, including both in healthy individuals and pain-related conditions (Rostron, Green, Kingsley, & Zacharias, 2021). This supports our findings that demonstrated that in active young adults with long standing hip/groin pain, when adjusting for age, sex and BMI, greater volume of the lateral hip muscles was associated with greater hip strength hip strength across various directions. This was observed even when the muscle's primary function was not directly associated with the direction of strength measured. For example, we observed a substantial relationship between the volume of gluteus medius and gluteus minimus and hip adduction strength. It is possible that individuals with larger lateral hip muscles may also have other larger muscles in their lower limbs, leading to increased overall strength and potentially explaining the multiple strength relationships observed in this study.

Although previous studies have shown that there are differences in muscle volumes between males and females (Belzunce, Henckel, Di Laura, & Hart, 2022; Douma et al., 2023; Marcon et al., 2016), the relationship between muscle volume and strength in individuals with hip/groin pain has not been reported. Our results did not find an interaction effect between sex and volume-strength relationships, indicating that the relationship in individuals with hip/groin pain may not be influenced by sex.

4.2. Lateral hip muscles

Previous research has functionally divided gluteus maximus into upper and lower portions based on its origin (Cowan et al., 2020; Grimaldi, Richardson, Durbridge, et al., 2009). The upper portion is believed to have more of an abductor role, while the lower portion is more related to extension, with both portions contributing to external rotation (Grimaldi, Richardson, Durbridge, et al., 2009; Reiman et al., 2012). Although we did not partition gluteus maximus, our results showed that its muscle volume had the strongest relationship with hip abduction, followed by extension and external rotation, as expected.

The primary function of the gluteus medius is to perform hip abduction and contribute to pelvic stabilisation during single leg stance. Its antagonist relationship with hip adduction may explain why after abduction, gluteus medius had its strongest relationship with hip adduction strength. Recent evidence has highlighted the contribution of the posterior fibres of the gluteus medius to external rotation of the hip joint, which could explain its association with hip external rotation strength in our study (Al-Hayani, 2009; Neumann, 2010; Semciw et al., 2013). Additionally, it is thought that the anterior fibres play a role in internal rotation (Semciw et al., 2013). The internal rotation torque potential of gluteus medius and minimus, specifically the anterior portions, markedly increases with hip flexion (Neumann, 2010).

The gluteus minimus muscle is a critical contributor to several hip movements, including abduction, internal rotation, and femoral head stabilisation (Beck, Sledge, Gautier, Dora, & Ganz, 2000; Semciw et al., 2014). Notably, this muscle exhibits a unique anatomical arrangement, with some of its fibres attaching to the anterior and superior hip capsule. This close association with the hip joint allows the gluteus minimus to perform both locomotion and stabilisation functions around the hip (Al-Hayani, 2009; Beck et al., 2000; Flack et al., 2014; Semciw et al., 2014). Given the important function of gluteus minimus, it is not surprising that we found moderate to substantial relationships between muscle volume and hip strength.

The TFL, together with gluteus medius and minimus, flexes and internally rotates the femur and together with gluteus maximus abducts the hip through the iliotibial band (Hébert et al., 2011; Mosler et al., 2018; Thorborg, Petersen, Magnusson, & Hölmich, 2010). Interestingly, in our study, among the lateral hip muscles examined, the TFL demonstrated the weakest associations with hip strength. Furthermore, we observed no associations between muscle volume and strength for hip adduction or either direction of rotation. This finding may be explained by the fact that hip rotation strength was measured in prone with neutral hip flexion, which may not provide a mechanical advantage for the TFL. This may have led to a length-tension mismatch and reduced the moment arm, thereby potentially reducing the capacity of the TFL to generate force (Neumann, 2010). Therefore, joint position should be carefully considered when interpreting hips muscle strength measurements and their relationships with muscle volume/MFI.

4.3. Intramuscular fat infiltration

In people with hip pain, higher MFI in the gluteal muscles has been found in the painful side compared to the asymptomatic side and asymptomatic controls (Cowan et al., 2020; Lawrenson et al., 2019). Consistent with these findings, our study observed variations in the distribution of MFI across the lateral hip muscles. However, contrary to expectations, we did not identify a significant association between MFI and hip strength measurements. Despite this, the localised accumulation of MFI, particularly in the anterior segments of the gluteus medius and gluteus minimus, as well as in multiple areas along the TFL, suggests that specific regions within these muscles may be more prone to MFI. This disparity in fat distribution could have clinical relevance, potentially indicating areas of vulnerability or adaptive change in response to chronic hip/groin pain, even in the absence of a direct link to muscle strength as measured in our study.

It is important to note that our study participants, who were sports-active individuals, may have been in the early stages of hip/groin pain presentation and not yet functionally impaired to the extent where MFI would significantly influence hip strength measures. Additionally, our cohort consisted of relatively young individuals, which may have resulted in a relatively low variance in MFI. Previous studies have indicated a positive relationship between age and higher levels of MFI (18, 59). By acknowledging the characteristics of our study participants and the potential variations in MFI among different populations, future studies could explore how factors like age, levels of physical activity, and athletic background (ranging from recreational to semi-elite) might influence MFI and its impact on muscle function in healthy individuals with those with hip/groin pain.

Previous research has shown that hip strength assessment can effectively differentiate between athletes with and without hip/groin pain (Mosler, Weir, Hölmich, & Crossley, 2015; Thorborg et al., 2018). Our research demonstrates that hip muscle size is associated with hip muscle strength and should therefore be considered in people with longstanding hip/groin pain. However, impairments of individual hip muscles may go undetected through strength testing alone. By combining strength tests with assessments of muscle size and MFI, a greater understanding of deficits in muscle structure and function can be achieved.

4.4. Limitations

There are several limitations to consider when interpreting the findings of this study.

Firstly, the cross-sectional design limits our ability to infer causality or temporality in the observed relationships. Secondly, only individuals with longstanding hip/groin pain were included which may limit the generalisability of our results to acute injuries. Thirdly, our strength assessments were limited to isometric make tests using handheld dynamometry, and alternative methods of measuring strength may produce different results. Finally, our results are based on hip/groin populations that are still participating in sports, potentially not representing those who have stopped participating due to their pain or symptoms. Additionally, as a planned prospective cohort study, there is a possibility of selection bias within our sample. The exclusion of individuals with more severe symptoms or those scheduled for surgery within the next two years may limit the generalisability of our results to a broader population.

Future studies should address these limitations by including larger and more diverse populations, using more precise strength measures, and investigating the relationship between muscle size, MFI, and hip strength over time.

5. Conclusion

Our study provides important insights into the association between hip muscle volume/MFI and hip muscle strength in active young adults with longstanding hip/groin pain. Our results revealed that greater lateral hip muscle volume is positively associated with greater hip strength, with gluteus maximus and minimus volume exhibiting the most consistent relationships with hip strength in multiple directions.

Ethical statement

Ethical Approval: This study was conducted in accordance with the ethical guidelines and regulations set forth by La Trobe University Human Ethics Committee (HEC) under protocols HEC 15e019 and HEC 16–045, as well as the University of Queensland Human Ethics Committee under protocols 2015000916 and 2016001694.

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Declaration of competing interest

None. All authors declare that they have no competing interests to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2023.11.007.

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