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Hip abductor muscle volumes are smaller in individuals affected by patellofemoral joint osteoarthritis

D.C. Ackland † *, M. Denton ‡, A.G. Schache ‡ §, M.G. Pandy ‡, K.M. Crossley §

† *Department of Biomedical Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia*
‡ *Department of Mechanical Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia*
§ *School of Allied Health, La Trobe University, Bundoora, Victoria 3083, Australia*

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SUMMARY

Objective: The aims of this study were twofold: firstly, to compare hip abductor muscle volumes in individuals with patellofemoral joint (PFJ) osteoarthritis (PFJ OA) against those of healthy controls; and secondly, to determine whether hip muscle volumes and hip kinematics during walking are related in individuals with PFJ OA and healthy controls.
Methods: Fifty-one individuals with PFJ OA and thirteen asymptomatic, age-matched healthy controls ≥40 years were recruited. Volumes of the gluteus medius, gluteus minimus and tensor fasciae latae were obtained from magnetic resonance (MR) images. Video motion capture was used to measure three-dimensional hip joint kinematics during overground walking.
Results: Significantly smaller gluteus medius ($P = 0.017$), gluteus minimus ($P = 0.001$) and tensor fasciae latae ($P = 0.027$) muscle volumes were observed in PFJ OA participants compared to controls. Weak correlations were observed between smaller gluteus minimus volume and larger hip flexion angle at contralateral heel strike (CHS) ($r = -0.279$, $P = 0.038$) as well as between smaller gluteus minimus volume and increased hip adduction angle at CHS ($r = -0.286$, $P = 0.046$).
Conclusion: Reduced hip abductor muscle volume is a feature of PFJ OA and is associated with increased hip flexion and adduction angles during the late stance phase of walking for PFJ OA participants and healthy controls.

Introduction

The patellofemoral joint (PFJ) is the compartment of the knee most commonly affected by symptomatic osteoarthritis (OA)[1], and can contribute substantially to limitations in physical function associated with knee OA[2]. Individuals with isolated PFJ cartilage damage are 5.8 times more likely to develop cartilage damage in the tibiofemoral joint (TFJ) than those without damage[3], with isolated symptomatic PFJ OA shown to be a possible marker for future development of TFJ OA and thus a focus for the early management of knee OA[4]. While the structure and function of the PFJ is distinctly different to that of the TFJ, it is thought that rehabilitation strategies for individuals affected by PFJ OA ought to be tailored to this joint to improve clinical outcomes; however, there is limited knowledge of modifiable impairments associated with PFJ OA that may potentially be targeted by therapeutic interventions.

Hip abductor muscle weakness is a consistent feature of PFJ pain, and has been implicated in the development and progression of PFJ pathologies[5,6]. A systematic review of twenty-four studies concluded that men and women with patellofemoral pain syndrome (PFPS) have lower isometric hip muscle strength compared to pain-free individuals[6]. Greater femoral adduction can result from hip abductor muscle weakness, which could theoretically increase the lateral forces acting on the patella due to a larger angle formed between the quadriceps tendon and the patellar tendon in the frontal plane, i.e., the quadriceps angle (Q-angle)[7]. Such a scenario may result in high contact pressures on the lateral patella leading to the onset of PFJ symptoms[5,8–10]. If greater PFJ contact loading contributes to the development or progression of PFJ OA, then improving the strength of the hip abductor muscles may represent a

* Address correspondence and reprint requests to: D. Ackland Department of Biomedical Engineering, University of Melbourne Parkville, Victoria, Australia, 3010. Tel: 61-3-8344-8646.

E-mail addresses: dackland@unimelb.edu.au (D.C. Ackland), mjdenton2@gmail.com (M. Denton), anthonys@unimelb.edu.au (A.G. Schache), pandym@unimelb.edu.au (M.G. Pandy), k.crossley@latrobe.edu.au (K.M. Crossley).

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modifiable factor in the management of PFJ OA. While it is plausible that hip abductor weakness may influence PFJ OA development and progression, the majority of evidence for such a relationship comes from studies investigating PFPS[11]. Although some overlap may exist between these two conditions from a biomechanical perspective[12], evidence supporting hip abductor weakness in people with PFJ OA remains unclear[13].

We have recently demonstrated that people with PFJ OA walk with increased hip adduction and decreased hip extension during late stance compared to aged-matched controls[14]. While reduced hip abductor muscle strength may be responsible for the increased hip adduction observed during walking, there is currently little evidence linking altered movement patterns during walking with muscle dysfunction in people with PFJ OA. Since a muscle's capacity to generate peak isometric muscle force is a function of its volume[15], a muscle's volume may be used as an indicator of its force-generating capacity or strength. The aims of the present study were therefore twofold: firstly, to compare the volumes of the hip abductors (specifically, the gluteus medius, gluteus minimus and tensor fasciae latae muscles) in individuals with PFJ OA against those of healthy controls; and secondly, to determine whether a relationship exists between hip muscle volumes and hip kinematics during walking in individuals with PFJ OA and healthy controls. We hypothesized that: (1) hip abductor muscle volumes would be lower for people with PFJ OA compared to healthy controls; and (2) lower hip abductor muscle volume would be associated with greater hip adduction motion during the stance phase of walking.

Materials and methods

Participants

Fifty-one individuals with symptomatic and radiographic PFJ OA were recruited as a subgroup from a larger randomized controlled trial, as well as thirteen asymptomatic, age-matched controls with no evidence of lower limb pathologies. All participants were over 40 years of age. The eligibility criteria for the PFJ OA participants were derived from a previously defined study protocol[16] and included anterior or retro-patellar knee pain severity of $\geq$4 on an 11-point numerical pain scale during at least two PFJ loading activities: squatting, stair ambulation, rising from sitting, with symptoms present on most days during the preceding month. Radiographic severity of OA was assessed using the Kellgren and Lawrence (KL)[17] grading system, adapted to assess the PFJ using skyline X-rays[2]. Inclusion into the OA group required a KL score of $\geq$1 in the lateral PFJ. Participants were excluded if they presented with moderate to severe concomitant tibiofemoral OA (KL score of >2 on a posterior-anterior radiograph) or if medial patellar KL radiographic PFJ OA severity was more severe than lateral patellar KL radiographic PFJ OA severity. Participants in the control group were required to be physically active and free from lower-limb complaints, including radiographic evidence of knee OA (KL score = 0 for all compartments). Exclusion criteria for participants in both groups included: previous major surgery (arthroplasty or osteotomy, but not arthroscopy); knee injections (within 3 months); previous or ongoing physiotherapy for knee pain (within 12 months); planned lower-limb surgery (following 6 months); history of hip or knee fractures; current condition affecting the ability to walk normally; concomitant pain from other knee structures, hips, ankles, feet or lumbar spine; major medical conditions (including neurological or nerve conditions); fibromyalgia; allergy to adhesive tapes; contraindications for magnetic resonance (MR) imaging; and a body mass index (BMI) of $\geq$35 kg m^{-2}.

Demographic characteristics were recorded for participants in both groups, including age, gender, height, weight and BMI. Disease characteristics including radiographic severity of tibiofemoral OA (TKL), medial patellar KL and lateral patellar KL, the Physical Activity Score for the Elderly (PASE)[18] and the Knee injury and Osteoarthritis Outcome Score (KOOS)[19] were assessed for each individual in the OA group. Ethical approval for this study was granted by the University of Melbourne Human Ethics Advisory Group and the Department of Human Services Radiation Safety committee, Victoria. Written informed consent was obtained from all participants prior to study commencement.

Measurement of hip abductor muscle volume

MR imaging was performed on the most symptomatic leg for the PFJ OA participants and the dominant leg for the healthy controls. During imaging, participants assumed a supine position with both knees fully extended and legs strapped together. MR images were obtained from a Siemens (Erlangen Germany) 3T Trio MR scanner using a T2-weighted fat-suppressed (water excitation) MEDIC (multi-echo data image combination) gradient echo sequence (TE = 12 ms, TR = 23 ms, NEX = 1, Flip angle 12°, 155 Hz/Px, Parallel imaging GRAPPA 2) with a voxel size of 1 mm × 1 mm × 1 mm. Slice thickness was 1 mm, with no gaps between slices. The entire pelvic region was imaged, from the sacral promontory to the inferior aspect of the pubic arch (approximately 200 slices). The average acquisition time was approximately 20 mins per participant. Datasets that contained movement artefact were discarded.

The volumes of the gluteus medius, gluteus minimus and tensor fasciae latae were measured from axial MR images using commercially available image processing software (Amira FEI 5.3.3, FEI Visualization Sciences Group, Bordeaux, France). Muscles were segmented by semi-automatically digitising individual muscle cross-sectional areas (CSA) on each axial MR image[20] (Fig. 1). This process was repeated for every transverse slice through the muscle belly, from its proximal origin to distal insertion, and excluded fat. To estimate total muscle volume, CSAs of each axial slice were summed and multiplied by slice thickness. All segmenting was performed by a single unblinded investigator.

A test/retest reliability study was performed to assess the intra-investigator repeatability of the muscle volume measurement technique. Five randomly selected participants (4 PFJ OA, one control) were evaluated on two separate occasions, at least 1 month apart. The investigator was blind to the previous results during the retest. The reliability coefficients obtained for gluteus medius (ICC = 0.997), gluteus minimus (ICC = 0.999) and tensor fasciae latae (ICC = 1.000) demonstrated excellent repeatability of the measurements. Furthermore, the standard error of measurement (SEM) was acceptably low (gluteus medius 0.84 cm^3; gluteus minimus 0.57 cm^3; tensor fasciae latae 0 cm^3).

Gait experiments

Lower limb kinematic data during walking were recorded on all participants as described previously[14], and only a brief description is provided here. Three-dimensional locations of retro-reflective markers were measured using a 9-camera video motion analysis system (Vicon, Oxford Metrics Ltd., Oxford) sampling at 120 Hz as participants walked at their self-selected speed. Marker trajectories were filtered using a low-pass, fourth-order Butterworth filter with a cut-off frequency of 10 Hz. Ground reaction force data were simultaneously recorded using three instrumented force platforms (AMTI Inc., Watertown, MA) sampling at 1080 Hz and used to identify major gait events such as foot-strike and toe-off. Three-dimensional hip joint angles were calculated using a 7-segment biomechanical model implemented in BodyBuilder software (Vicon, Oxford Metrics Ltd.,

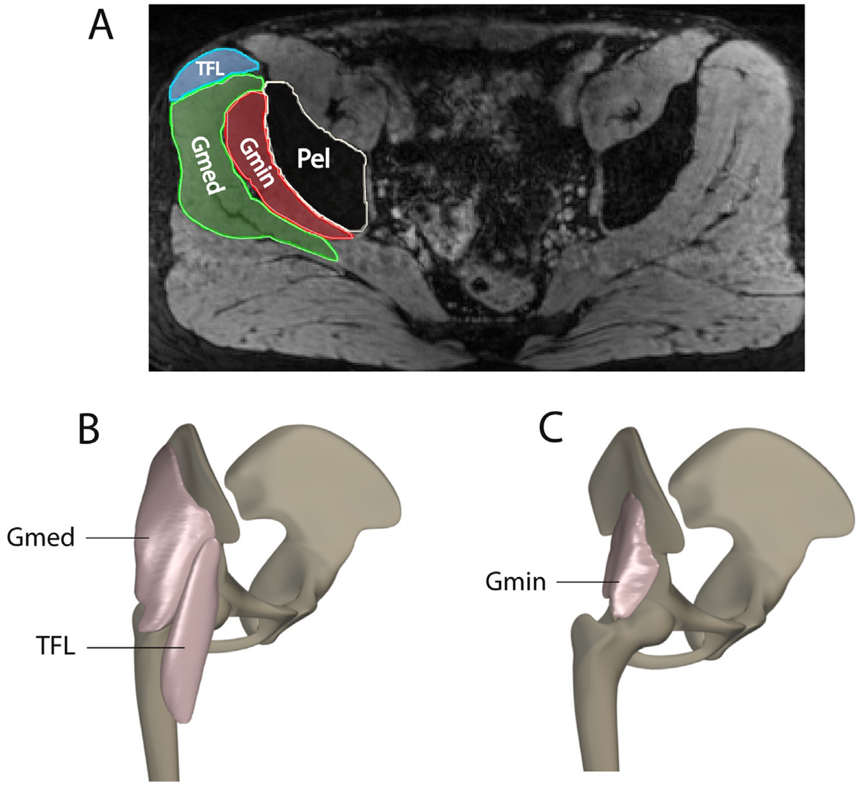

Fig. 1. Representative axial magnetic resonance (MR) image of the pelvis showing delineation of the pelvis, gluteus medius, gluteus minimus and tensor fasciae latae (A) and 3D muscle rendering of segmented MR images for gluteus medius and tensor fasciae latae (B) and gluteus minimus (C). Symbol definitions are as follows: Pel, pelvis; Gmin, gluteus minimus; Gmed, gluteus medius; TFL, tensor fasciae latae.

Oxford)[21]. The location of the hip joint centre was estimated using the predictive approach of Harrington *et al.* (2007)[22]. Anatomical reference frames for the pelvis and femur were consistent with previously published definitions (see Table III in Schache and Baker[23]). The hip joint coordinate system was defined as per ISB recommendations[24]. Data were collected over three successive gait trials for each participant.

Data analysis

Chi square tests were used to assess the influence of demographic characteristics on muscle volumes. Pearson correlation coefficients were calculated between demographic variables (age, gender) and the normalised muscle volumes of gluteus medius, gluteus minimus and tensor fasciae latae, with muscle volume data normalised to body weight ($cm^3.kg^{-1}$) in the PFJ OA participants and healthy controls. Correlation coefficient values above 0.5 were considered "strong", between 0.3 and 0.5 "moderate" and below 0.3 "weak"[25]. Normality of muscle volume data was verified using the Shapiro–Wilk test.

Paired *t*-tests were used to investigate differences in muscle volumes between the PFJ OA participants and controls, with equality of variances between groups verified. An analysis of co-variances (ANCOVA) was then used to quantify between-group differences in normalized muscle volumes. Age and gender were included as co-variates in the ANCOVA to determine how they contributed to variations in the reported muscle volumes. Using data from the entire cohort, Pearson correlation coefficients were then employed to assess the relationship between normalized muscle volume and selected kinematic variables, including values for hip joint flexion-extension, adduction-abduction and internal-external rotation angles at the time of contralateral toe off (CTO) and contralateral heel strike (CHS). All discrete kinematic variables for each participant were averaged across the three gait trials. Between-group differences in the kinematic variables were assessed using paired *t*-tests. Data were analyzed with the Statistical Package for the Social Sciences (PASW Statistics 18, SPSS Inc., Chicago, IL).

Results

Participant demographics

The OA group ($n = 51$; age $= 55 \pm 10$ years, body weight $= 76 \pm 13$ kg, BMI $= 27 \pm 4$ kg m^{-2}) and control group ($n = 13$; age $= 52 \pm 5$ years, body weight $= 71 \pm 13$ kg, BMI $= 25 \pm 3$ kg m^{-2}) were matched for all demographic characteristics ($P > 0.05$). The ratio of females to males was 32:19 for the PFJ OA group and 8:5 for the control group, with no statistically significant differences in gender frequency between the two cohorts ($\chi^2 = 0.001$; $p = 0.976$). Of the PFJ OA participants, 18%, 14% and 38% had a lateral patellar KL score of four, three and two, respectively (Fig. 2). In contrast, 0%, 12%, and 34% of PFJ OA participants had a medial patellar KL score of four, three and two, respectively. Strong correlations were demonstrated between body weight and muscle volume for gluteus medius ($r = 0.768$, $p < 0.001$) and gluteus minimus ($r = 0.595$, $p < 0.001$), while a moderate correlation was observed for tensor fasciae latae volume ($r = 0.456$, $p = 0.001$).

Muscle volumes and OA severity

A weak but statistically significant correlation was demonstrated between female gender and smaller normalised muscle volume for gluteus medius in the PFJ OA participants and controls ($r = -0.245$, $p = 0.05$), while a moderate correlation was observed between female gender and smaller normalised gluteus minimus

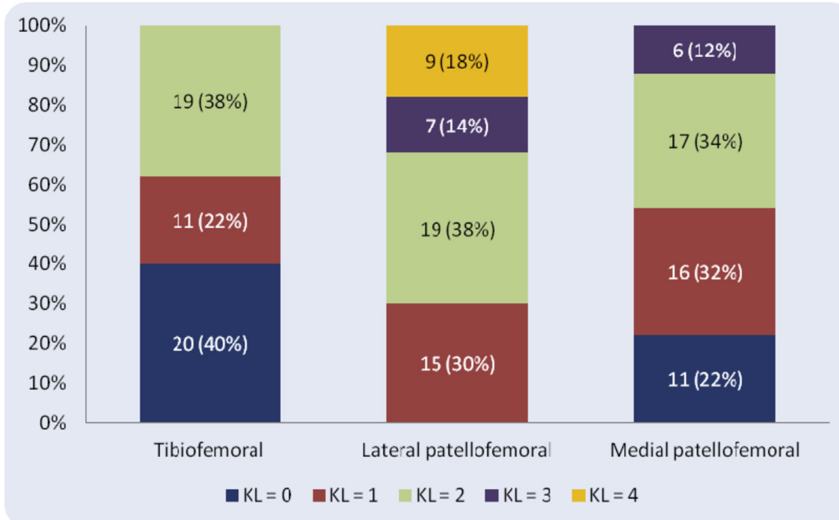

Fig. 2. Compartmental distribution and radiographic grade of knee osteoarthritis in patellofemoral joint (PFJ) OA participants ($n = 51$). Values reported as number of participants (percentage of total cohort). Kellgren and Lawrence (KL) scores for osteoarthritis severity are provided (Kellgren *et al.*, 1957). A higher score corresponds to increased osteoarthritis severity: KL = 0 (no osteoarthritis), KL = 1 (osteoarthritis doubtful), KL = 2 (minimal osteoarthritis), KL = 3 (moderate osteoarthritis), KL = 4 (severe osteoarthritis).

volume ($r = -0.359$, $p = 0.052$) (Table I). There was a weak but statistically significant correlation observed between increasing age and smaller normalised muscle volume for gluteus minimus ($r = -0.251$, $p = 0.046$).

Between-group comparisons of mean normalised hip abductor muscle volumes using *t*-tests revealed significantly smaller volumes in PFJ OA participants compared to controls (Table II). The differences were 0.47 $cm^3\ kg^{-1}$ ($P = 0.017$), 0.21 $cm^3\ kg^{-1}$ ($P = 0.001$) and 0.21 $cm^3\ kg^{-1}$ ($P = 0.027$) for the gluteus medius, gluteus minimus, and tensor fasciae latae, respectively. Including gender and age as co-variants using ANCOVA did not substantially change the results (gluteus medius, $p = 0.015$; gluteus minimus, $p < 0.001$; tensor fasciae latae, $p = 0.023$).

Table I
Correlations between normalised muscle volumes and subject age, gender, presence of patellofemoral joint (PFJ) osteoarthritis (PFJ OA), radiographic severity of OA in the lateral patellofemoral joint (LPKL), and radiographic severity of OA in the medial patellofemoral joint (MPKL). Correlations are given for gluteus medius, gluteus minimus and tensor fasciae latae, and *p*-values provided in parentheses immediately below. One, two and three asterisks indicate a significant correlation at the $P < 0.05$, $P < 0.01$ and $P < 0.001$ level, respectively

Muscle	Age	Gender	PFJ OA	LPKL	MPKL
Gluteus medius	−0.028	−0.245	−0.288*	−0.355*	−0.126
	(0.828)	(0.050)	(0.021)	(0.011)	(0.380)
Gluteus minimus	−0.251*	−0.244	−0.421**	−0.512***	−0.450**
	(0.046)	(0.052)	(0.001)	(<0.001)	(0.001)
Tensor fasciae latae	−0.013	−0.153	−0.278*	0.075	0.100
	(0.916)	(0.232)	(0.027)	(0.604)	(0.491)

Muscle volume associations with hip kinematics

A weak negative correlation was observed between the hip flexion angle at CHS and gluteus minimus muscle volume, i.e., an increased hip flexion angle (or less hip extension) was associated with a smaller muscle volume ($r = -0.279$, $p = 0.038$) (Table III). There was also a weak negative correlation between the hip adduction angle at CHS and gluteus minimus muscle volume, i.e., an increased hip adduction angle was associated with a smaller muscle volume ($r = -0.286$, $p = 0.046$). There were no other statistically significant correlations between hip joint kinematic variables and hip abductor muscle volumes. Compared to controls, people with PFJ OA walked with a significantly larger hip flexion angle at CHS (mean difference: 7.0°, 95% confidence interval (CI): [2.3, 11.6], $p = 0.004$), as well as a significantly larger hip adduction angle at CHS (mean difference: 3.1°, 95% CI: [0.5, 5.7], $p = 0.019$) and a significantly larger hip external rotation angle at CTO (mean difference: 6.7°, 95% CI: [0.1, 13.2], $p = 0.047$).

Discussion

The PFJ is the knee compartment most commonly affected by OA, and is a clinically significant source of knee OA symptoms[26]. A population-based study of adults with knee pain showed a distribution of OA for the combined TFJ/PFJ, isolated PFJ and isolated TFJ of 40%, 24% and 4%, respectively[1]. While non-invasive treatment options in the management of TFJ OA are established and include knee bracing, taping, use of insoles, and manual therapy[27], little is

Table II
Averaged muscle volumes of gluteus medius, gluteus minimus and tensor fasciae latae for the PFJ osteoarthritis (PFJ OA) and control groups. Muscle volume and muscle volume normalized to subject mass are given, along with standard deviations (SD). Significant differences ($P < 0.05$) in normalized muscle volume between the PFJ OA subjects and control subjects, when controlling for age and gender, are indicated

Muscle	Subject	Muscle Volume (cm^3)	Normalised Muscle Volume (cm^3/kg)	
Gluteus medius	PFJ OA	305.4 (67.1)	4.0 (0.6)	$P = 0.017$
	Control	289.9 (44.0)	4.5 (0.8)	
Gluteus minimus	PFJ OA	71.6 (19.5)	1.0 (0.2)	$P = 0.001$
	Control	73.5 (11.7)	1.1 (0.2)	
Tensor fasciae latae	PFJ OA	62.9 (22.9)	0.8 (0.3)	$P = 0.027$
	Control	64.6 (22.2)	1.0 (0.4)	

Table III
Correlations between hip joint kinematics parameters and normalized gluteus medius, gluteus minimus and tensor fasciae latae muscle volumes. Correlation data are provided with *p*-values given immediately below in parentheses. Asterisk indicates a significant correlation at the $P < 0.05$ level

Joint kinematics parameter	Gluteus medius	Gluteus minimus	Tensor fasciae latae
Hip flexion angle, value at CTO	0.084	−0.034	−0.043
	(0.538)	(0.802)	(0.757)
Hip flexion angle, value at CHS	−0.145	−0.279*	−0.113
	(0.286)	(0.038)	(0.41)
Hip adduction angle, value at CTO	−0.059	−0.151	0.096
	(0.668)	(0.266)	(0.485)
Hip adduction angle, value at CHS	0.092	−0.268*	−0.125
	(0.498)	(0.046)	(0.363)
Hip internal rotation angle, value at CTO	−0.020	0.094	−0.018
	(0.881)	(0.489)	(0.895)
Hip internal rotation angle, value at CHS	0.035	0.095	−0.106
	(0.799)	(0.486)	(0.440)

known about the features associated with PFJ OA that may be potentially modifiable and a target of therapeutic intervention. The objectives of this study were to compare volumes of the hip abductors in individuals with PFJ OA against those of healthy controls, and determine whether hip muscle volumes and hip kinematics during walking are related.

We found that people with PFJ OA had statistically significantly smaller gluteus medius, gluteus minimus, and tensor fasciae latae muscle volumes compared to those of healthy, aged-matched controls. Statistically significant correlations were observed between gluteus minimus volumes and hip joint angles at CHS during walking; specifically, those who had smaller gluteus minimus muscle volumes tended to display increased hip flexion and adduction angles at CHS during walking. These results are consistent with our hypothesis that hip abductor muscle volumes are smaller in individuals with PFJ OA, and suggest that weakness of the hip abductor muscles is a feature of PFJ OA. It is possible that an increase in the lateral component of the quadriceps line of pull (Q-angle) occurs with an increased hip adduction angle, which in cadaveric studies has been shown to increase PFJ contact pressures[9] and lateral patellar displacement[10], and may therefore play a role in the development of PFJ OA.

The smaller hip abductor muscle volumes observed in the PFJ OA group suggests that these individuals may have reduced force-producing capacity in these muscles, contributing to the observed correlations with increased hip adduction angles during walking compared to aged-matched controls. Smaller hip abductor muscle volumes may explain the greater hip adduction angle during the late stance phase of walking for PFJ OA participants reported by Crossley *et al.* (2018)[14]. In late stance, the ground reaction force, and hence the load transmission at the knee and PFJ, is at a peak before it decreases quickly following CHS[28]. Our observed relationship between smaller gluteus minimus muscle volume and increased hip adduction angle during walking suggests that this muscle may play an important role in modulating hip function in late stance. While we observed a statistically significant difference in gluteus medius and tensor fasciae latae muscle volumes between PFJ OA participants and controls, we did not find tensor fasciae latae or gluteus medius muscle volumes to be correlated with hip joint kinematics during walking.

The difference in muscle volume between people with PFJ OA and healthy controls was more pronounced for gluteus minimus than for gluteus medius, despite gluteus minimus having approximately one quarter of the volume of gluteus medius. A study investigating the differential atrophy of hip musculature after prolonged bed-rest found that the rate of volume-loss in gluteus minimus was approximately three times greater than that of gluteus medius[29]. It is possible that anatomical differences between the two muscles may contribute to their distinct activation patterns[30], and therefore the degree of muscle atrophy. For instance, gluteus medius has a longer moment arm than that of gluteus minimus[31], and each muscle may be represented by multiple sub-regions of varying architecture, activation and function[32]. Because gluteus medius can produce a greater amount of torque for a given muscle force, it is a more efficient hip abductor than gluteus minimus, and thus may be preferentially activated in these individuals.

There are a number of limitations associated with this study. Firstly, the results indicate an association between muscle volume and PFJ OA; however, being a cross-sectional study, it is not possible to determine the temporal relationship between muscle size and PFJ OA. While it is possible that hip abductor weakness has a role in the pathogenesis of PFJ OA, it is equally plausible that individuals with this condition experience disuse atrophy of these muscles due to compensatory changes in gait or reduced activity as a pain-limitation strategy. Longitudinal studies are required to ascertain the role of hip muscle size in the etiology and progression of PFJ OA. Secondly, the original KL rating for radiographic OA severity[17] did not include the PFJ and thus a modified version[2] was required for the current study. This scale was applied in preference to the OARSI atlas[33], as it takes into account both joint space narrowing and osteophytes severity in a single score. Diagnosis was also made on the basis of symptoms, in particular the presence of pain in the PFJ area when aggravated by PFJ loading activities. To reduce the chance of concomitant tibiofemoral OA contributing to these symptoms, participants with confirmed tibiofemoral OA (KL ≥ 2) were excluded. Thirdly, the sample size for the control group was chosen to be as large as could be practically achieved within the time and resource constraints, and consequently the control group included much fewer participants ($n = 13$) than our PFJ OA cohort ($n = 51$). This difference reflected the difficulties in recruiting an older population from the general community with no knee or other lower-limb complaints, who were physically active with no radiographic knee OA, and who had the time and inclination to attend both radiographic and biomechanical evaluations. Nevertheless, our sample size calculations revealed that we had sufficient study power to detect significant between-group differences in muscle volumes at the $P < 0.05$-level, despite the discrepant sample sizes. Finally, differences in PFJ OA between the ipsilateral and contralateral lower limbs, and possible asymmetry in muscle volumes and joint function during locomotion, were not quantified but ought to be explored in future research.

The results of the current study suggest that having larger volume hip abductor muscles may be important for the management of PFJ OA. Therefore, interventions aimed at strengthening hip muscles may represent a promising approach to address functional impairments associated with PFJ OA. As targeted gait retraining and hip muscle strengthening programs have achieved successful treatment outcomes in individuals with PFPS[34–38], future investigations into the impact of these interventions in individuals with PFJ OA may be justified.

In conclusion, we found that individuals with PFJ OA have smaller gluteus medius, gluteus minimus and tensor fasciae latae muscle volumes when compared with healthy controls. Gluteus minimus is a substantially smaller muscle than gluteus medius and thus has a relatively lower capacity to abduct the hip and support the body against gravity[39]; however, a smaller gluteus minimus muscle volume was associated with increased hip flexion and adduction angles during the late stance phase of walking. A smaller muscle volume results in a reduced capacity for a muscle to generate force and thus, may be considered an indicator of muscle weakness. These results provide evidence for a possible relationship between hip abductor muscle weakness and functional impairments as a consequence of PFJ OA. While it remains unclear whether hip abductor weakness is a cause or an effect of PFJ OA, the current study provides recommendations for hip muscle strengthening interventions for people with PFJ OA, as well as several directions for future research into this relationship.

Author contributions

DA: data analysis, manuscript writing; MD, image analysis and manuscript drafting; AS, gait experiments, data analysis and drafting of manuscript; MP, drafting of manuscript; KC, data analysis and interpretation, manuscript drafting.

Conflict of interest

There are no other financial interests that any of the authors may have, which could create a potential conflict of interest or the appearance of a conflict of interest with regard to this study.

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