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TITLE

Deep hip muscle activation during squatting in femoroacetabular impingement syndrome

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ABSTRACT

Background: Deep hip muscle retraining is a common objective of non-operative management for femoroacetabular impingement (FAI) syndrome. These muscles are considered to have an important role in hip joint stabilization, however, it is unclear whether their function is altered in the presence of hip pathology. This exploratory study aimed to investigate activation patterns of the hip muscles during two squatting tasks in individuals with and without FAI syndrome.

Methods: Fifteen individuals with FAI syndrome (symptoms, clinical examination and imaging) and 14 age- and sex-comparable healthy controls underwent testing. Intramuscular fine-wire and surface electrodes recorded electromyographic activity of selected deep and superficial hip muscles during the squatting tasks. Activation patterns from individual muscles were compared between-groups using a wavelet-based linear mixed effects model ($P<0.05$).

Findings: There were no between-group differences for squat depth or speed during descent or ascent for either task. Participants with FAI syndrome exhibited patterns of activation that differed significantly to controls across all muscles ($P<0.05$) when squatting using their preferred strategy. Unlike controls, participants with FAI syndrome exhibited a pattern of activation for obturator internus during descent that was similar in amplitude to ascent, despite the contrasting contraction type (i.e. eccentric vs concentric).

Interpretation: Individuals with FAI syndrome appear to implement a protective strategy as the hip descends towards the impingement position. Future studies should examine patients prospectively to establish whether these strategies are counterproductive for pathology and warrant rehabilitation.

Key Words: neuromuscular; electromyography; contraction; hip joint; pain.

INTRODUCTION

The deep hip external rotator and extensor muscles are considered to have an important role in hip joint stabilization (1). The function of these muscles may be altered in the presence of hip pathology, which could have implications for intra-articular loading and joint tissue health (2). Femoroacetabular impingement (FAI) syndrome, a motion related condition of the hip joint, is associated with hip pain and impaired function in younger active adults (3). Treatments for FAI syndrome are suboptimal (4, 5), likely due, in part, to an incomplete understanding of the neuromuscular alterations associated with the condition.

Diagnosis of FAI syndrome, defined through a combination of symptoms, clinical signs, and morphological features (6), is increasing, however hip muscle function in these patients has not been well studied. Retraining of deep hip muscle function (e.g. quadratus femoris, obturator internus, piriformis) is a common objective of non-operative management (7) and post-operative rehabilitation (8) for FAI syndrome. Although experimental evidence suggests that activation of these deep muscles may contribute to dynamic hip stability (9-11), it is unclear if adaptations in neuromuscular control are associated with FAI syndrome. An understanding of deep hip muscle function in FAI syndrome is needed to inform targeted treatments.

Few studies have investigated deep hip muscle function in any context (9-12). Findings from the only investigation of FAI syndrome demonstrated altered coordination of deep hip muscle activity compared to healthy controls during walking (13), despite the generally pain-free nature of this task without requirement for hip motion into an impingement position (deep hip flexion, combined with hip adduction and internal rotation). Unlike healthy controls, individuals with FAI syndrome exhibited tightly constrained activation of the deep hip external rotator muscles,

which is interpreted as a strategy to control the hip during early swing, and plausibly enhance protection for the hip as it initiated movement into flexion (13). As the mechanical actions of the deep hip external rotator and extensor muscles directly oppose impingement (2), exploration of tasks that require motion towards a potentially provocative, impinging position is likely to further characterize FAI-related neuromuscular adaptations.

Squatting challenges the hip into impingement, is used for the evaluation of lower limb function (14), and is frequently prescribed in rehabilitation following surgery for FAI syndrome (15). Hip muscle activity during squatting has not been investigated in FAI syndrome but may provide further insight into any neuromuscular alterations. This exploratory study aimed to investigate activation patterns of the hip muscles during two squatting tasks: (i) an unconstrained deep squat where participants could use their preferred strategy to reach maximum depth; and (ii) a constrained squat designed to encourage deep hip flexion without allowing for compensation from the trunk or pelvis (16), in individuals with FAI syndrome and an asymptomatic control group without FAI syndrome. On the basis of previous work (13) and task design, we hypothesised that individuals with FAI syndrome would exhibit altered deep hip muscle activation during squat descent to enhance protection for the hip as it approached the impingement position, and this might be exaggerated by reduced potential to compensate with other segments (i.e. trunk, pelvis) during a constrained squat.

METHODS

Participants

Fifteen volunteers (24.7 ± 4.9 years; 76.0 ± 11.8 kg) diagnosed with FAI syndrome (cam, or combined cam and pincer morphology) were recruited to participate in this cross-sectional study. Potential participants were identified by screening the surgical records of the study orthopaedic surgeon (JO). Participants who presented with symptoms, tested positive for a clinical impingement test (17), and had definitive signs of cam, or combined cam and pincer morphology on imaging ((X-ray and/or magnetic resonance imaging (MRI)); alpha angle $>55^\circ$ (cam morphology) (18), and lateral centre edge angle $>39^\circ$ and/or positive crossover sign (combined cam and pincer morphology) (19)) were included. All participants were scheduled for surgery. Individuals diagnosed with bilateral FAI syndrome were tested on the more symptomatic side. Participants were excluded if they presented with: (i) pincer morphology alone (20); (ii) history of hip surgery; (iii) other lower limb injury/pain sufficient to limit function in the preceding month; (iv) moderate or severe radiographic OA; or (v) other forms of arthritis, diabetes, cardiac or circulatory conditions.

Fifteen healthy control participants (27.1 ± 4.5 years; 72.6 ± 11.6 kg) with no history of hip or groin pain, or lower limb surgery were recruited from the community. Control participants were comparable to the FAI syndrome group with respect to age, sex and leg dominance. Control participants underwent a standard MRI of their study hip to ensure they did not have cam, or combined cam and pincer morphology. The oblique sagittal plane was used to measure the alpha angle, a measure of asphericity at the femoral head-neck junction (21); the coronal plane was used to measure the lateral centre edge angle; the localizer sequence was used to correct for pelvic obliquity (21). Angles were measured using OsiriX imaging software (Pixmeo SARL, Switzerland) and the Orthopaedic Studio v1.2 Plugin (Spectronic AB, Helsingborg, Sweden).

Participants with alpha angles $<50^\circ$ and centre edge angles $<40^\circ$, considered to represent joint structure free of cam or pincer morphology (18, 19), were eligible to participate.

This study used a subset of participants enrolled in other studies (13, 16). Participants provided written informed consent. This study was approved by the Human Research Ethics Committee at The University of Melbourne. One control participant was unable to undergo MRI and was excluded.

Procedures

Participants completed the squatting tasks wearing standardized footwear (Dunlop Volley, Pacific Brands, Melbourne, Australia). Motion analysis data were collected using a Vicon MX 12-camera motion analysis system (Oxford, UK) at 120 Hz; two embedded force platforms (AMTI Inc., Watertown, MA, USA) collected ground reaction force data at 3000 Hz (for data presented elsewhere (16)).

Electromyography (EMG) was recorded with a Noraxon DTS 2400 wireless telemetry system (Noraxon, Scottsdale, USA) from eight muscles of the study limb (imaged hip for control participants). Surface electrodes were placed over the muscle bellies of semimembranosus (SM), upper gluteus maximus (UG), sartorius (SR), and tensor fascia latae (TF). The skin was cleaned with alcohol and shaved to reduce impedance prior to attaching Ag/Ag-Cl electrodes (10 mm diameter; Covidien, Kendall foam electrodes, Dublin, Ireland). Electrodes were placed in a bipolar configuration (inter-electrode distance: 20 mm) along the orientation of muscle fibres. Intramuscular electrodes recorded activity from select deep hip external rotator muscles: posterior gluteus medius (GM), piriformis (PI), obturator internus (OI), and quadratus femoris (QF). Bipolar fine-wire EMG electrodes were fabricated from 75 μ m Teflon-coated stainless steel

wire (22). Wires were threaded into a hypodermic needle (Terumo, Somerset, USA, 0.65 x 70 mm); 1 mm of insulation was removed to form the recording surface; exposed tips were bent back at 1.5 and 4 mm to form hooks. Fine wire electrodes were inserted under ultrasound guidance. Standard sterile procedures were used. EMG signals were pre-amplified 500 times and low pass filtered, then wireless-transmitted for output via Noraxon DTS Analog Module. Signals were digitized with 16-bit resolution at 3000 sample/s using the Vicon analog-to-digital converter. A pre-set fixed 312 ms wireless transmission delay was implemented and corrected in analysis.

For both squatting tasks (16), participants stood with feet parallel and shoulder width apart. Each foot was positioned on a firm foam wedge (Slant by OPTP, Minneapolis, USA); the heels of both feet were in approximately 30° of plantar flexion. The wedges were used to encourage deep hip flexion, unrestricted by ankle dorsiflexion range of motion, which is reduced in FAI syndrome patients prior to surgery (23). Participants were instructed to maintain an even distribution of weight between feet, hold their straight arms to the front (horizontal) for balance, and use their preferred strategy to squat as deeply as possible at a self-selected controlled pace. Squats included three phases: (i) descent from a standing position to the end of self-chosen available range; (ii) a 3-second hold; and (iii) ascent to an upright standing position. The constrained squat included the addition of a vertical pole positioned anterior to the trunk. Participants were instructed to maintain an upright trunk and descend parallel to the pole. The constrained squat was designed to minimize forward trunk lean and pelvic anterior-posterior tilt, and consequently, encourage greater hip flexion without compensation by trunk flexion (16). In cases where forward trunk lean was observed by the tester during descent, additional trials were performed. After demonstrating proficiency, participants completed five trials for each squat.

The international Hip Outcome Tool (iHOT-33) (24) and the Copenhagen Hip and Groin Outcome Score (HAGOS) (25) (0 = extreme hip and/or groin problems, 100 = no hip and/or groin problems) were used to assess physical function in participants with FAI syndrome. A modified Tegner Activity Scale (0 = disability, 10 = competitive sport at the professional level) was administered to grade level of physical activity in all participants (26). Participants rated their hip pain during each squatting task on an 11-point numerical rating scale (NRS) (0 = no pain, 10 = worst pain imaginable).

Data Analysis

Descent speed, ascent speed, and squat depth were measured for each trial using the test-leg hip joint centre. Maximum squat depth was defined as the lowest point reached by the test-leg hip joint centre during the task (27), subtracted from its maximum height from the floor while standing, and normalized as a percentage of leg length (distance between medial malleolus and anterior superior iliac spine). EMG data were high-pass filtered at 50 Hz and 20 Hz, for fine wire and surface EMG, respectively, with a dual-pass, zero-lag fourth order Butterworth filter. EMG signals for all squatting trials were visually inspected for artefacts. Trials without acceptable signal-to-noise ratios were excluded (28). EMG data were rectified and smoothed using a 6 Hz dual-pass, zero-lag fourth order, low-pass Butterworth filter. EMG was selected over a single squat cycle and then spline interpolated to 200 time points (descent=80, hold=40, ascent=80). EMG data from both squatting tasks were subsequently amplitude-normalized to the mean of the peak values (29) during the ascending phase of the unconstrained squat. Data analysis was undertaken using Matlab, version 2016a (The Mathworks, Inc., Natick, USA) and Microsoft Excel, version 15.22 (Microsoft Corporation, 2016).

Statistical Analysis

Data were assessed for normality by inspecting Q-Q plots and using Shapiro-Wilk tests and log transformed where necessary. Demographic and spatiotemporal variables were compared between groups using independent t-tests or Pearson's chi-square. Activation patterns were compared between groups for each squat using a wavelet-based linear mixed effects model based on the technique of wavelet functional ANOVA (wfANOVA) (30). This technique allows for comparison between features of the activation patterns. Time- and amplitude-normalized data were transformed into the wavelet domain using a fourth order Symlets wavelet with periodic extension. The Symlets wavelet was compared against all orthogonal wavelets available within the Matlab toolbox (Matlab, version 2016a), and demonstrated superior fit for activation patterns from all muscles (>89%). A wavelet-based compression of the data inherently reduces the number of significant P-values, and consequently increases statistical power. To reduce the number of comparisons, and further increase statistical power, only the 1st level wavelet approximation coefficients were extracted. These coefficients tend to represent global characteristics of the muscle recordings, which emerge from summation of many individual motor units, and are likely to relate primarily to muscle force and movement (31). Between-group differences were tested *post hoc* using Fisher's least significant difference test. Significant between-group differences calculated in the wavelet domain were transformed back to the time domain for interpretation.

A contraction ratio was calculated to compare activation levels during the descent and ascent phases of the squat tasks. First, in order to account for variations in slope, time- and amplitude-normalized EMG data from each phase were divided into three temporally equal sub-phases. Second, mean values were calculated for each sub-phase and summed to obtain a single contraction value for the squatting phase. Individual contraction ratios were then calculated as

contraction during descent divided by the sum of contraction during descent and contraction during ascent. Thus, a ratio of 0.5 would equate to equal contraction during the descent and ascent phases. Participant contraction ratios, averaged across squatting trials, were compared between-groups for each task using independent t-tests. Matlab, version 2016a (The Mathworks, Inc., Natick, USA) and Statistical Package for the Social Sciences (SPSS), version 24 (IBM, New York, USA) were used for statistical analyses. Significance level was set at $P < 0.05$.

RESULTS

Participant characteristics of FAI and control groups were comparable (Table 1). Eight participants in the FAI group (53%) had bilateral FAI syndrome. Symptom duration for FAI participants averaged 28 months (range 5-48). Physical activity level (Tegner activity scale) was significantly lower in the FAI group at the time of testing ($P = 0.04$). Nine FAI participants (60%) reported some pain on the NRS (≥ 1) in the study hip during unconstrained (range 1-8) and constrained (range 1-6) squatting tasks. Pain levels were not significantly different between tasks ($P = 0.8$). There were no between-group differences for squat depth or speed during descent or ascent for either task (Table 2).

Unconstrained squat

During both descent and ascent, individuals with FAI syndrome exhibited patterns of activation that differed significantly to controls across all muscles ($P < 0.05$) (Figure 1). First, relative to peak activation in ascent, activation of GM and OI was higher in FAI participants than controls during descent. The analysis also shows differences in specific features of the EMG burst pattern of other muscles (Figure 1). First, GM EMG has an earlier reduction in amplitude after its peak

in ascent. Second, activation of PI reached its peak later during descent in FAI than controls. Unlike the other external rotator muscles (GM, OI and PI), the activation pattern of QF was similar for both groups during descent, though activation increased at a slower rate in FAI participants during ascent (Figure 1).

For the hip flexor muscles, individuals with FAI syndrome exhibited a pattern of TF activation characterised by greater difference between baseline activation and peak activation during descent and ascent compared to controls, who demonstrated only a minor change in amplitude in both phases. Activation of SR reduced to a minimum level earlier during ascent in FAI than controls (Figure 1). For the extensor muscles, activation of SM reduced from peak during the hold phase by a greater amount in the control than FAI participants. The activation pattern of UG reached its peak earlier during ascent in FAI syndrome than controls (Figure 1). When the amplitude of EMG was compared between ascent and descent, the FAI group had a significantly higher contraction ratio for OI than controls (mean difference 0.08 [95% CI 0.16 to 0.002], $P = 0.04$) (Figure 2), which indicates less difference between activation levels during descent and ascent than for the control group. A similar tendency was observed for GM, PI and QF, though between-group differences did not reach statistical significance (Figure 2).

Constrained squat

During the constrained squat, the overall pattern of EMG of GM, PI and QF was similar for both groups (Figure 3). The activation pattern of OI demonstrated activity during descent, similar to the amplitude during ascent in FAI, which is counterintuitive considering the eccentric action of this muscle during the descent phase. This observation differed from the lower amplitude of OI activation during descent than ascent for controls ($P < 0.05$) (Figure 3). Similar to the

unconstrained squat, individuals with FAI syndrome exhibited greater difference between baseline activation and peak activation of TF during descent and ascent compared to controls (Figure 3). Activation of SR relative to the peak of the unconstrained ascent was lower during periods of the hold in FAI than controls (Figure 3). The pattern of SM activation appeared more similar between groups in the constrained squat, but compared to the peak activity in the unconstrained squat (Figure 1), activation of SM was lower in controls than FAI syndrome during some periods of the descent and ascent phases (Figure 3). Activation of UG during ascent was higher relative to peak in the unconstrained task for the FAI group than controls (Figure 3). Consistent with the pattern features described above, the contraction ratio for OI in the FAI group was higher than controls and equal to 0.5, implying equal activation during descent and ascent, despite the contrasting contraction modes (i.e. eccentric vs concentric) (Figure 2).

DISCUSSION

Participants with FAI syndrome exhibited patterns of activation that differed significantly to controls across all muscles when squatting using their preferred strategy. The key observation was that participants in the FAI group had less differentiation of activation between squatting phases, and elicited similar levels of activation for most deep hip muscles regardless of the associated eccentric or concentric task demands. Lower amplitudes of EMG are typically expected during the eccentric phase. In direct contrast to this, the contraction ratio for the FAI syndrome participants demonstrated almost equal activation during decent (eccentric) and ascent (concentric) phases. This may point towards a protective strategy as the hip descends towards a

potentially provocative impinging position. This tendency was exaggerated when participants were prevented from using pelvic and trunk motion to contribute to the task (constrained squat).

Activation of GM and OI were higher in FAI syndrome than controls during the descending phase of the unconstrained squat (Figure 1). As expected by the force-velocity relationship, there was a general observation of higher peak activation of deep hip and primary extensor muscles during ascent (when muscles were shortening) than descent (when muscles were lengthening). As EMG was normalized to the dynamic peak, it is not possible to directly compare amplitude between groups. Interpretation would be influenced by between-group differences in peak activation level during ascent. However, examination of the unprocessed EMG signals provided no evidence for higher *peak* activation during ascent in participants with FAI syndrome (data not presented). Nevertheless, activation of GM and OI is more similar between ascent and descent than would be expected by the force-velocity relationship, as shown for the control group. A feature of muscle activation specific to the FAI group was the later peak of PI EMG during descent compared to controls. The small cross-sectional area and moment arm lengths of PI and OI indicate that their torque generation capacity is likely to be small (12). However, these deep muscles, in addition to posterior GM, have a high proportion of fibre length to cross-sectional area, allowing for production of significant force over small changes in length. These anatomical specifications could suggest suitability for active stabilization of the head of femur within the acetabulum (1, 32). Altered activation patterns of these deep hip external rotator muscles during descent in individuals with FAI syndrome could be interpreted as a protective strategy to stabilize the joint (although perhaps unnecessarily given the intrinsic stability of the hip) and reduce pain provocation as the hip approaches impingement.

Consistent with their altered EMG pattern features, participants with FAI syndrome had a significantly higher contraction ratio than controls for OI. A tendency toward a similar pattern (albeit not statistically significant) was evident for GM and PI (Figure 2). The derived contraction ratio allows for comparison between activation levels during the descending and ascending phases. The spatial and temporal characteristics of EMG recordings from our controls coincide with the limited available published data for GM and PI from healthy young adults ($n=10$) during a squat task (33). Recruitment is ~50% higher during ascent (33), which reflects the physiological necessity of greater activation to generate the same torque when a muscle is contracting concentrically (34). Our data suggest that, unlike individuals with healthy, pain-free hips, individuals with FAI syndrome elicit similar levels of activation for OI regardless of contraction type (i.e. eccentric vs concentric). With hip joint stabilization, OI has an advantageous line of force, giving it some capacity to produce external rotation (35) and enhance joint compression (2). However, given that the torque generation capacity of OI is minimal, sustained activation may be further evidence of a strategy to protect the injured hip joint from impingement and pain provocation (36).

When participants with FAI syndrome were constrained to perform the squatting task in a specific manner, OI was the only deep hip external rotator muscle that differed significantly to controls. The activation pattern of OI in FAI syndrome demonstrated EMG amplitude during descent that was similar to that during ascent (Figure 3). Though this observation was consistent across both tasks, it was exaggerated when the task was constrained, where activation was, on average, equal across phases (contraction ratio = 0.5) (Figure 2). Altered activation during descent may relate to the lower hip external rotation joint moment we previously identified in this cohort during the same task (16). Interestingly, activation of UG was higher relative to peak

in the unconstrained task during ascent for the FAI group than controls (Figure 3). This observation suggests that individuals with FAI syndrome may require greater contribution from the primary extensor muscles to maintain pelvis alignment when biomechanical solutions for task performance are restricted.

Irrespective of squat type, participants with FAI syndrome exhibited greater difference between baseline activation and peak activation of TF during both descent and ascent (Figures 1, 2). This has different interpretations. It could either mean that unlike the sustained activation of controls, individuals with FAI syndrome have more burst-like activation, or that controls have trivial increase in activation above baseline (and therefore little variation across the task) and FAI syndrome have a more substantial activation, that peaks near maximal squatting. Our normalization to peak precludes conclusion of which interpretation is more likely. Lamontagne et al. (37) reported 32% less variation of TF EMG (which equated to reduced activation) during squatting descent in FAI syndrome compared to controls. Casartelli et al. (38) reported lower *absolute* EMG for TF in individuals with FAI syndrome compared to controls during a maximum voluntary contraction task. Until further data are available, these findings are difficult to reconcile, but differ from the current existing clinical hypotheses which propose almost-universal overactivity of TF in individuals with several different hip pain conditions (39). However, given that TF activation would promote flexion and impingement, overactivity would be counterproductive for FAI syndrome. TF is considered a primary hip abductor given its insertion into the iliotibial band (2). Our biomechanical analysis identified that participants in the FAI group squatted with more contralateral pelvis drop, conceivably to avoid deeper hip flexion (16), which may relate to the observed difference in TF activation. Given that TF also contributes to hip flexion (2, 12), less sustained activation may mitigate potentially provocative

compression in the anterosuperior aspect of the hip joint, where the lesion is commonly located (3).

Findings from this cross-sectional exploratory study should be used to inform future research that is appropriately powered to test treatment targets. In order for evidence-based management strategies to be developed, longitudinal research is required to establish the effects of altered hip muscle function on symptoms and structural joint health in individuals with FAI syndrome. This invasive study is limited by a small sample size and activation patterns were only acquired from a subset of hip muscles. Further, EMG data were normalized to the mean of the dynamic peak and this normalization does not allow for interpretation of absolute level of EMG activity, and consequently no inferences can be made regarding magnitude of muscle force. Future research could aim to apply computational neuromusculoskeletal modelling techniques to estimate the force production of muscles surrounding the hip and the associated intra-articular joint loads.

CONCLUSIONS

Findings suggest that individuals with FAI syndrome do not discriminate between descent and ascent with respect to activation of a range of hip external rotator muscles, and appear to implement a protective strategy as the hip descends towards the impingement position. Future studies should examine patients prospectively to establish whether these strategies are counterproductive for pathology and warrant rehabilitation.

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FIGURE CAPTIONS

Figure 1. Ensemble average (± 1.96 *standard error) electromyographic (EMG) patterns for control (n=14) (blue) and femoroacetabular impingement (FAI) syndrome (n=15) (red) participants over an unconstrained squatting cycle (top). EMG data are normalized to the mean of the peak during the ascent phase for each muscle across the unconstrained squatting trials. Average between-group differences (FAI group mean minus control group mean; green) (± 1.96 *standard error) and significant between-group differences ($P < 0.05$) (black) over an unconstrained squatting cycle (bottom). SM - semimembranosus; UG – upper gluteus maximus; SR - sartorius; TF - tensor fasciae latae; GM - gluteus medius; PI - piriformis; OI - obturator internus; QF - quadratus femoris.

Figure 2. Ensemble average (+ standard deviation) contraction ratios for control (CON) (n=14) (blue) and femoroacetabular impingement (FAI) syndrome (n=15) (red) participants during unconstrained (left) and constrained (right) squatting tasks. Contraction ratios are calculated as the mean normalized activation during descent divided by the sum of the mean normalized activation during descent and the mean normalized activation during ascent. A ratio of 0.5 indicates equal contraction during descent and ascent phases. SM - semimembranosus; UG - gluteus maximus; SR - sartorius; TF - tensor fasciae latae; GM - gluteus medius; PI - piriformis; OI - obturator internus; QF - quadratus femoris; *- $P < 0.05$.

Figure 3. Ensemble average (± 1.96 *standard error) electromyographic (EMG) patterns for control (n=14) (blue) and femoroacetabular impingement (FAI) syndrome (n=15) (red) participants over a constrained squatting cycle (top). EMG data are normalized to the mean of the peak during the ascent phase of the unconstrained squat for each muscle across the constrained squatting trials. Average between-group differences (FAI group mean minus control group mean; green) (± 1.96 *standard error) and significant between-group differences ($P < 0.05$) (black) over a constrained squatting cycle (bottom). SM - semimembranosus; UG – upper gluteus maximus; SR - sartorius; TF - tensor fasciae latae; GM - gluteus medius; PI - piriformis; OI - obturator internus; QF - quadratus femoris.

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ACCEPTED MANUSCRIPT

Conflict of interest

The authors declare no conflict of interest.

ACCEPTED MANUSCRIPT

Table 1. Participant characteristics of the femoroacetabular impingement (FAI) syndrome (n=15) and control (n=14) groups.

Characteristic	FAI syndrome group	Control group
Age (years)	24.7 (4.9)	27.1 (4.5)
Males, n (%)	11 (73%)	10 (71%)
Height (m)	1.76 (0.09)	1.77 (0.08)
Body mass (kg)	76.0 (11.8)	72.6 (11.6)
Body mass index (kg/m ²)	24.4 (2.5)	23.2 (1.9)
FAI type (cam:combined)	11:4	
Side tested, n (%) dominant	10 (67%)	9 (64%)
Physical activity level (Modified Tegner Scale) [¶]	5.2 (2.1)	6.6 (1.0)*
The international Hip Outcome Tool (iHOT-33) [†]	51.9 (23.0)	
Copenhagen Hip and Groin Outcome Score (HAGOS) [†]		
Symptoms	53.6 (21.0)	
Pain	66.5 (18.2)	
ADL	70.3 (22.8)	
Sport	49.6 (19.5)	
Participation	33.3 (26.2)	
QOL	41.7 (20.1)	
Pain during squats ^δ		
unconstrained squat	1.9 (2.4)	0.2 (0.8)*
constrained squat	1.9 (2.3)	0.1 (0.5)*

Values are mean (standard deviation) unless otherwise stated; *P < 0.05; [¶]Tegner scale is 0-10 with zero representing disability and 10 representing competitive sport at the professional level; [†]iHOT-33 and HAGOS scores range between 0-100 with zero representing extreme hip and/or groin problems and 100 representing no hip and/or groin problems; ^δNumerical Rating Scale ranges between 0-10 with zero representing no pain and 10 representing worst pain possible; ADL, activity of daily living; QOL, quality of life.

Table 2. Squatting variables for femoroacetabular impingement (FAI) syndrome (n=15) and control (n=14) groups during unconstrained and constrained squatting tasks.

Variable	Unconstrained Squat			Constrained Squat		
	FAI syndrome group	Control group	P-value	FAI syndrome group	Control group	P-value
Descent speed (m/s)	0.48 (0.17)	0.58 (0.14)	0.08	0.33 (0.13)	0.35 (0.08)	0.56
Ascent speed (m/s)	0.55 (0.20) ^δ	0.69 (0.32) ^δ	0.16	0.38 (0.12)	0.45 (0.14)	0.16
Max squat depth (% leg length)	40.6 (11.7)	49.0 (17.5)	0.14	26.6 (11.1) ^δ	29.7 (6.7) ^δ	0.18

Values are mean (standard deviation); ^δlog transformed.

Highlights

- Hip muscle activation is altered during squatting in FAI syndrome.
- Activation of external rotators is similar in descent and ascent in FAI syndrome.
- Neuromuscular strategy appears protective as hip approaches impingement.
- Unclear whether these strategies are counterproductive and warrant rehabilitation.

Figure 1

Figure 2

Figure 3