Lower limb biomechanics in femoroacetabular impingement syndrome: a systematic review and meta-analysis

Matthew G King,[1] Peter R Lawrenson,[2] Adam I Semciw,[1,2] Kane J Middleton,[1] Kay M Crossley[1]

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[1]La Trobe Sport and Exercise Medicine Research Centre, School of Allied Health, College of Science, Health and Engineering, La Trobe University, Bundoora, Victoria, Australia
[2]School of Health and Rehabilitation Sciences, University of Queensland, Brisbane, Queensland, Australia

Correspondence to
Professor Kay M Crossley, La Trobe Sport and Exercise Medicine Research Centre, School of Allied Health, La Trobe University, Bundoora, VIC 3086, Australia; k.crossley@latrobe.edu.au

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ABSTRACT

Objective (1) Identify differences in hip and pelvic biomechanics in patients with femoroacetabular impingement syndrome (FAIS) compared with controls during everyday activities (eg, walking, squatting); and (2) evaluate the effects of interventions on hip and pelvic biomechanics during everyday activities.

Design Systematic review.

Data sources Medline, CINAHL, EMBASE, Scopus and SPORTDiscus until February 2017.

Methods Primary aim: studies that investigated hip or pelvic kinematics and/or joint torques of everyday activities in patients with FAIS compared with the asymptomatic contralateral limb or a control group. Secondary aim: studies that evaluated effects of conservative or surgical interventions on patients with FAIS using pre-post or controlled clinical trial designs. Biomechanical data must have been collected using three-dimensional motion capture devices. Reporting quality was assessed using the Epidemiological Appraisal Instrument and data were pooled (standardised mean difference (SMD), 95% CI) where populations and primary outcomes were similar.

Results Fourteen studies were included (11 cross-sectional and three pre/post intervention), varying between low and moderate reporting quality. Patients with FAIS walked with a lower: peak hip extension angle (SMD −0.40, 95% CI −0.71 to −0.09), peak internal rotation angle (−0.67, 95% CI −1.19 to −0.16) and external rotation joint torque (−0.71, 95% CI −1.07 to −0.35), and squatted to a lesser depth with no difference in hip flexion range. Pre/post intervention data were limited in number and quality, and to surgical cohorts.

Conclusion This review suggests that patients with FAIS may demonstrate hip biomechanical impairments during walking and squatting, with minimal literature available to comment on other tasks.

Clinical relevance The information presented in the review provides insight into the biomechanical differences associated with FAIS; however, the between-group differences were small to moderate. This information may aid in the development of management strategies for people with the condition.

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INTRODUCTION

Femoroacetabular impingement syndrome (FAIS) is a motion-related condition with a complex presentation of morphology, symptoms and clinical signs.[1] It is associated with the development of labral tears[2 3] and an increased risk of hip osteoarthritis (OA).[4] Recent recommendations from the Warwick agreement concluded that FAIS has a complex presentation and can only be diagnosed with the presence of assessment findings, symptoms in positions of impingement (flexion and internal rotation) and variances in bony hip morphology.[1] Pincer morphology is characterised by overcoverage of the acetabulum, whereas cam morphology is characterised by an increase in bone formation at the femoral head-neck junction.[5] The presence of morphological changes without clinical signs and symptoms is not considered to be FAIS,[1] and does not dictate that the individual will develop FAIS.[6] Cam morphology has been reported in up to 60%–90% of athletic populations.[7–10] However, the factors that delineate those who develop symptoms and those who do not are unclear. Since FAIS is a movement-related condition, biomechanical impairments associated with FAIS may play a role in symptom development and persistence, as well as structural joint deterioration.

Biomechanical impairments have been described in patients with FAIS but few syntheses have been performed. A recent systematic review concluded that patients with FAIS had lower range of motion (ROM) into positions of impingement.[11] However, the review was based on few available studies and meta-analyses were not conducted to pool study findings. Since the completion of the search strategy in 2013, additional studies investigating the biomechanics during everyday activities in patients with FAIS have been reported.

The best treatment options for those with FAIS are unknown. Arthroscopic surgery is increasingly popular, and intends to treat patients with FAIS by restoring the femoral head-neck offset[12] to regain function and relieve symptoms. However, the rates of arthroscopy are increasing despite the lack of supporting evidence.[13] The effects of surgical or conservative interventions on biomechanical impairments are not clear. Therefore, the aims of this systematic review were to: (1) identify differences in hip and pelvic biomechanics in patients with FAIS compared with controls during everyday activities (eg, walking and squatting); and (2) evaluate the effects of interventions on hip and pelvic biomechanics during these activities.

METHODS

The systematic review protocol was developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement[14] and was registered on the PROSPERO register (http://www.crd.york.ac.uk/PROSPERO/) (2016:CRD42016038677).

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Search strategy

A comprehensive search was conducted in Medline, CINAHL, EMBASE, Scopus and SPORTDiscus from the earliest date until February 2017. The search strategy was developed around two concepts with MeSH and keywords (limited to title and abstract) adapted to individual databases (Population: FAIS; keyword examples: 'femoroacetabular impingement', 'cam impingement', 'pincer impingement'. Outcome: biomechanics; keywords: 'kinetics', 'kinematics', 'biomechanics') (online supplementary A). Articles were imported into Endnote V.X7 and duplicates removed. Two reviewers (MGK and PRL) independently reviewed the title and abstracts of the Endnote library, and disagreements were resolved by consensus, or a third reviewer (AIS). After title and abstract screening, full-text articles of potentially suitable studies were obtained to determine their eligibility. Reference checking, citation tracking in Scopus and manual searching of ahead-of-print listing in journals of included papers were conducted to ensure all relevant studies were included.

Selection criteria

For the primary aim, studies were eligible if they included participants with FAIS and compared data with healthy controls, or the contralateral asymptomatic limb. For the secondary aim, studies were included if they evaluated the effect of a conservative or surgical intervention on patients with FAIS. This included single group pre-post designs where baseline scores were available for comparison with post-intervention scores. It also included cross-sectional studies where post-intervention scores of one group were compared with outcomes of a group who did not undergo any specific intervention. Included studies must have collected kinematic or joint torque data during activities using three-dimensional motion capture devices. Kinematic data must have been reported as means, peaks or total ROM and joint torque data must have been reported as means, peaks or impulses. Where duplicates of published data existed, the study with the larger sample size was included. Opinion pieces, editorials, narrative reviews, systematic reviews, case studies, book chapters, conference abstracts and studies published in a language other than English were excluded.

Reporting quality

Included studies' reporting quality was rated using a modified version of the Epidemiological Appraisal Instrument (EAI).[15] The EAI is appropriate to assess the reporting quality of observational[15 16] and intervention studies.[15] Items that were not relevant to observational and pre/post intervention studies were removed. Items were scored as 'Yes' (2 points), 'Partial' (1 point), 'No' (0 point), 'Unable to Determine' (0 point) or 'Not Applicable'. The maximal obtainable score for an observational study was 54, and 66 for a pre/post intervention study. Included studies were given a rating of high, moderate or low reporting quality based on the following criteria: high, >70% score on the EAI; moderate, ≤70% and >50%; and low, ≤50%. Two reviewers (MGK and PRL) independently reviewed the studies against the items and where consensus could not be made, a third reviewer (AIS) independently reviewed the paper.

Data extraction

Information on study design, sample characteristics (eg, age, sex, inclusion criteria), hip and pelvic kinematics, and joint torques were extracted and entered into Excel by one reviewer (MGK) with a random selection of 50% of the extracted data checked by another reviewer (PRL). All kinematic and joint torque data were extracted during stance phase where possible and data that were reported in text as graphs were digitised and extracted using DigitizeIt (DigitizeIt, Braunschweig, Germany). For pre/post intervention studies that included data on asymptomatic controls, the pre-intervention and control data were extracted to address the primary outcome, whereas the pre/post intervention data were extracted for the secondary outcome. Where included studies reported subsets of data from a smaller sample of additionally published work, the data from the larger sample were taken. However, if the larger sample had incomplete data, the study with the smaller, but complete data set was used for meta-analysis. If necessary, authors were contacted for further information to confirm eligibility and facilitate accurate data extraction.

Data analysis

Extracted data on hip and pelvic kinematics, and joint torques were grouped according to planes of motion for all included studies. Torque data that were reported as internal moments were multiplied by −1 and reported as external moments for summary and analysis. Standardised mean differences (SMD) and 95% CIs were calculated for all variables analysed in the FAIS versus control population by dividing the difference between groups by the pooled SD. Where multiple studies were available, data were pooled in a meta-analysis using a random effects model (Review Manager V.5.3). To maintain sufficient clinical homogeneity for data pooling, studies were grouped according to population (eg, cam-only FAIS) and outcome (eg, peak hip extension). Cohen's criteria were used to interpret pooled SMD with a large effect defined as ≥0.8, moderate >0.5 and <0.8, and a small effect defined as ≤0.5 and ≥0.20.[17] Statistical heterogeneity was evaluated from pooled data using the I^2 statistic, where a value of 25%, 50% or 75% was considered low, moderate or high level heterogeneity, respectively.[18] In the event that data were unable to be pooled in a meta-analysis, a qualitative synthesis was conducted by reporting the SMD and 95% CI, along with the reporting quality. Where data were estimated from graphs of included studies, sensitivity analyses were conducted with the estimated data removed.

Subgroup analyses were conducted on data reported for patients with cam-only FAIS. Specifically, subgroups were defined as cam-only FAIS when the study's eligibility criteria included symptomatic patients with cam morphology and excluded those with combined (defined as an individual with both cam and pincer morphology in the same hip) or pincer-only morphology. A random effects model was used to pool the SMD and 95% CI to determine the effect. Due to the limited pre/post intervention data, only qualitative analyses were conducted.

Definitions of levels of evidence were adapted from van Tulder *et al*[19] and consistent with those used in previous reviews with similar included study types.[20–22] Allocation of levels of evidence were based on the reporting quality and defined as: (1) strong if the pooled data were statistically homogenous (P>0.05) and obtained from three or more studies of which two were classed as high quality; (2) moderate if the pooled data were obtained from three or more studies, which were statistically heterogeneous (P<0.05), and one of the studies was classed as high quality; or data pooled from multiple moderate/low quality, statistically homogenous studies; (3) limited if the data obtained were from one high-quality study; or two homogenous moderate/low quality studies; or multiple statistically heterogeneous moderate/low quality studies; (4) insufficient if the data were obtained from one moderate/low-quality study; (5) conflicting if the pooled data were not statistically significant and from multiple statistically heterogeneous studies with inconsistent findings.

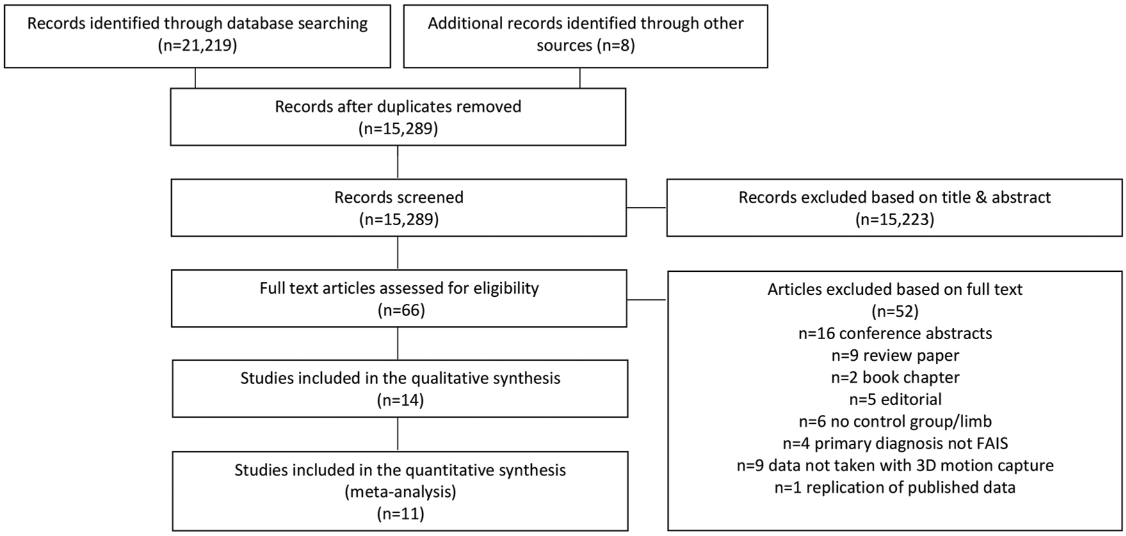

Figure 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) study selection flow chart. FAIS, femoroacetabular impingement syndrome.

RESULTS

Search strategy and reporting quality

The search strategy identified 21 227 articles for evaluation (figure 1). Following the removal of duplicates, 15 289 articles were evaluated for inclusion. Title and abstract screening excluded 15 223 and 66 full-text articles were assessed for eligibility with 14 meeting the inclusion/exclusion criteria. Of the 14 included studies, 11 were cross-sectional and three were pre/post intervention studies. All studies investigated the biomechanics associated with the primary diagnosis of FAIS. Two intervention studies included control and pre-intervention data and were therefore included in both aims. One study[23] presented some data that were a replication of a larger sample[24]; where the larger sample presented incomplete data, the smaller more complete data set was taken for the meta-analysis.

A total of 215 symptomatic patients (158 men, 57 women; mean age range 24.7–40.1 years) with the primary diagnosis of FAIS, as well as 236 controls (158 men, 78 women; 27.1–43.2 years) were included in the review (table 1 and 2). Seven of the 14 studies only included participants with cam-type FAIS (n=86, 56 men) and seven studies included a variety of cam, pincer and combined type FAIS. FAIS was diagnosed through X-ray, MRI or CT with alpha angle inclusion ranging from >50° to >60° for cam morphology and centre edge angle (CEA) inclusion ranging from >35° to >39° or a positive crossover sign for pincer morphology. No studies investigated the effects of conservative interventions and three case series studies evaluated the effects of surgical interventions on kinematics and joint torques.

Comparisons in biomechanics between FAIS and controls were described during walking,[12 23–29] squatting,[28 30–32] drop landing,[28] ascending stairs[12 33] and sit-to-stand.[34] Comparisons of pre/post intervention biomechanics were described during walking,[12 23] squatting[35] and ascending stairs.[12] Reporting quality score per item ranged from 0.82 to 1.37 with zero high, nine moderate and five low-quality studies (online supplementary B). All included studies reported their aims/hypothesis, participant characteristics, used standardised motion capture methods and adjusted for covariates where applicable. No included studies blinded observers or outlined assessment period.

FINDINGS

Walking sagittal plane hip kinematics: FAIS versus controls

Pooled data of sagittal plane kinematics showed moderate evidence of a small effect for lower peak hip extension angle (SMD −0.40, 95% CI −0.71 to −0.09; heterogeneity I^2=0%, P=0.60)[12 24 25 27 28] and moderate evidence of a moderate effect for total sagittal plane ROM (−0.51, 95% CI −0.93 to −0.08; I^2=0%, P=0.66)[12 26 28] but no difference (−0.19, 95% CI −0.47 to 0.08; I^2=0%, P=0.46) in peak hip flexion angle[12 24–28] (figure 2A) during stance in patients with FAIS compared with controls (figure 2A).

Two additional studies reported data on total ROM during a full walking cycle (ie, stance and swing phase),[23 25] pooled data provided limited evidence of a large effect that patients with FAIS walked with less total sagittal plane ROM compared with controls (−0.98, 95% CI −1.57 to −0.40; I^2=0%, P=0.43) (figure 2A).

Walking frontal plane hip kinematics: FAIS versus controls

Pooled data showed moderate evidence of no difference in peak hip adduction angle (−0.06, 95% CI −0.43 to 0.31; I^2=27%, P=0.24)[12 24 25 27 28] and peak hip abduction angle during stance (−0.29, 95% CI −0.77 to 0.20; I^2=57%, P=0.07)[12 24 26 27] (figure 2B). Total frontal plane ROM in stance was pooled from four studies, with moderate evidence (−0.31, 95% CI −0.84 to 0.23; I^2=50%, P=0.11) of no difference between FAIS and control groups[12 25 26 28] (figure 2B).

Qualitative synthesis of unpooled studies

One moderate quality study[25] investigated peak hip abduction angle in swing phase, with insufficient evidence of no between-group differences (SMD −0.55, 95% CI −1.29 to 0.20) (table 3). One low-quality study[23] reported data on frontal plane ROM in a full walking cycle. This review found insufficient evidence that patients with FAIS walked with less total frontal plane ROM compared with controls (−1.22, 95% CI −2.13 to −0.31) (table 3).

Walking transverse plane hip kinematics: FAIS versus controls

Pooled transverse plane kinematics demonstrated moderate evidence of a moderate effect for lower peak hip internal rotation angle (−0.67, 95% CI −1.19 to −0.16; I^2=47%, P=0.15)[12 25 27

Table 1 Summary of included cross-sectional studies

	FAIS group			Controls				
Author, year	**FAIS type**	**Inclusion criteria**	**Sample**	**Criteria**	**Sample**	**Comparability**	**Task**	**Reported differences in hip and pelvic kinematics and joint torques: FAIS compared with controls**
Bagwell *et al*, 2016[30]	Unilateral Cam only FAIS	▶ ≤45 years older ▶ Skeletally mature ▶ Unilateral hip pain with no OA ▶ α>50.5° (axial oblique MRI)	n=15 6 men Age 31.9 (7.6)	▶ Negative log roll ▶ <5 cm asymmetry FABER ▶ Nil pain passive hip internal rotation ▶ No hip or back pain ▶ No lower limb/back surgery ▶ α<50.5° (axial oblique MRI) ▶ CEA between 20° and 40°	n=15 6 men Age 32.7 (7.8)	Age Sex Mass	Squat	FAIS group squatted to a lesser depth with: ▶ Less mean hip flexor torque ▶ Greater anterior pelvic tilt at peak hip flexion and smaller peak femur flexion ▶ Smaller peak hip internal rotation angle
Diamond *et al*, 2016[25]	Cam or combined FAIS	▶ Positive impingement tests ▶ 3 months of hip/groin pain ▶ No history of hip surgery ▶ Kellgren-Lawrence grade <3 ▶ α>55° (oblique sagittal plane, MRI) AND/OR ▶ CEA>39° (coronal plane MRI)	n=15 11 men Age 24.7 (4.9)	▶ No history of hip or groin pain ▶ No previous hip surgery ▶ No morphological FAIS ▶ α<50°* (oblique sagittal plane MRI) ▶ CEA<40°* (coronal plane MRI)	n=14 10 men Age 27.1 (4.5)	Age Sex BMI Dominant leg	Walking	FAIS group walked with: ▶ Less total sagittal plane ROM in cycle
Hammond *et al*, 2017[33]	Cam, pincer or combined FAIS	▶ <40 years old ▶ Preoperative FAIS ▶ No previous lower limb surgery or radiographic OA ▶ Radiographic confirmation (angles/view NR)	n=20 15 men Age 27.6 (5.8)	▶ No hip or back pain (self-reported) ▶ No history of lower body injuries ▶ No history of hip OA	n=20 15 men Age 27.1 (5.0)	Age Sex Height BMI	Stairs	FAIS group completed stairs: ▶ With greater peak hip flexion moment
Hetsroni *et al*, 2015[26]	Cam or combined FAIS	▶ Men aged 18 years or older ▶ Insidious onset of hip pain ▶ Positive impingement sign and relieved after intra-articular injection ▶ Absence of lower limb injuries ▶ α>60° (view NR MRI) ▶ CEA between 25° and 40° (view NR, MRI)	n=15 15 men Age 33 (6)	▶ Men only aged 18 years or older ▶ Absent lower limb abnormalities on assessment ▶ Negative hip impingement test ▶ No lower limb injuries	n=15 (30 hips) 15 men Age 28 (6)	Sex BMI	Walking	FAIS group walked with: ▶ Greater sagittal plane pelvic ROM ▶ Smaller pelvic internal rotation angle at heel strike ▶ Smaller hip abduction angle at heel strike
Hunt *et al*, 2013[27]	Cam, pincer or combined FAIS	▶ Anterior groin pain ▶ Presentation consistent with FAIS ▶ Positive impingement sign ▶ No history of hip surgery ▶ No signs of OA ▶ MR arthrogram confirmation (angles/view NR)	n=30 25 men Age 28.4 (6.9)	▶ No lower limb extremity pain or dysfunction ▶ No previous hip surgery ▶ Negative impingement signs	n=30 20 men Age 27.5 (5)	Age Sex	Walking	FAIS group walked with: ▶ Smaller peak hip extension angle ▶ Smaller peak hip adduction angle ▶ Smaller peak hip internal rotation ▶ Smaller peak hip flexion and external rotation joint torque
Kennedy *et al*, 2009[24]	Unilateral cam only FAIS	▶ Positive impingement test ▶ No hip OA on X-ray ▶ α>50.5° (AP and Dunne X-ray)	n=17 10 men Age 35.5 (10.6)	▶ No history of serious lower limb injury or surgery ▶ No hip pain or stiffness ▶ No functional problems according to the WOMAC ▶ No hip OA on X-ray ▶ α NR (AP X-ray)	n=14 8 men Age 34.2 (9.5)	Age Sex BMI	Walking	FAIS group walked with: ▶ Less total sagittal plane hip ROM ▶ Less total frontal plane hip and pelvic ROM ▶ Smaller peak hip abduction angle

Continued

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Table 1 Continued

	FAIS group			Controls				
Author, year	**FAIS type**	**Inclusion criteria**	**Sample**	**Criteria**	**Sample**	**Comparability**	**Task**	**Reported differences in hip and pelvic kinematics and joint torques: FAIS compared with controls**
Kumar *et al*, 2014[28]	Unilateral cam only	▶ Positive impingement test ▶ No neurological disorders ▶ Able to undergo MRI ▶ α>55° (oblique axial MRI, AP and frog leg X-ray)	n=7 5 men Age 36.6 (9.7)	▶ No lower limb pain ▶ A history of no lower limb surgery or serious injury ▶ No neurological disorders ▶ Able to undergo MRI ▶ α and CEA NR (view NR, MRI)	n=8 8 men Age 27.3 (7.7)	Age Sex BMI	Walking Squat Drop landing	FAIS group squatted with: ▶ Greater peak hip adduction angle ▶ Greater peak hip external rotation torque
Lamontagne *et al*, 2009[31]	Unilateral cam only FAIS	▶ Positive impingement test ▶ No OA or joint space narrowing on X-rays ▶ α>50.5° (AP and Dunne X-ray)	n=15 9 men Age 35.3 (9.1)	▶ No history of lower limb injury ▶ No lower limb surgery ▶ No OA or joint space narrowing on radiographs ▶ α NR (AP X-ray)	n=11 6 men Age 34.5 (10.1)	Age Sex BMI	Squat	FAIS group squatted with ▶ Less total sagittal pelvic ROM
Ng *et al*, 2015[32]	Cam only FAIS	▶ Positive impingement test ▶ Plan to undergo orthopaedic surgery ▶ Hip pain ▶ No neurological/musculoskeletal injury ▶ BMI<30 kg/m² ▶ Radial α>60° (oblique axial CT) OR ▶ Axial α>50.5° (oblique axial CT)	n=12 12 men Age 38 (9)	▶ No clinical signs or symptoms ▶ No neurological or musculoskeletal or major lower limb injury/disorder ▶ BMI<30 kg/m² ▶ Radial α<60° (oblique axial CT) ▶ Axial α<50.5° (oblique axial CT)	n=14 14 men Age 32 (6)	Age Sex BMI	Squat	No reported differences
Samaan *et al*, 2017[34]	Cam, pincer or combined FAIS	▶ Positive FADIR test ▶ No joint replacements ▶ No previous lower limb surgery on test limb ▶ No hip OA ▶ BMI<35 kg/m² ▶ α>55° (oblique axial MRI and AP X-ray) OR ▶ CEA>35° (oblique axial MRI and AP X-ray)	n=17 13 men Age 40.1 (7.2)	▶ No joint replacements ▶ No previous lower limb surgery on test limb ▶ No hip OA ▶ BMI<35 kg/m² ▶ α NR (oblique axial MRI and AP X-ray) ▶ CEA NR (oblique axial MRI and AP X-ray)	n=31 17 men Age 41.4 (12.6)	Age Sex BMI	Sit-to-stand	No reported differences
Samaan *et al* 2017[29]	Cam, pincer or combined FAIS	▶ Positive FADIR test ▶ No joint replacements ▶ No previous lower limb surgery on test limb ▶ No hip OA ▶ α>55° (oblique axial MRI and AP X-ray) OR ▶ CEA>35° (oblique axial MRI and AP X-ray)	n=15 11 men Age 40.1 (7.5)	▶ No joint replacements ▶ No lower limb pain ▶ No hip OA ▶ Negative FADIR test ▶ Previous hip trauma ▶ α NR (oblique axial MRI and AP X-ray) ▶ CEA NR (oblique axial MRI and AP X-ray)	n=34 19 men Age 43.2 (12.4)	Age Sex BMI	Walking	FAIS group walked with: ▶ Larger hip flexion torque impulse

Age reported as means (SD); all joint torques listed as external.

*Control inclusion reported as alpha angles >50° and centre edge angles >40°. This was considered an error.

AP, anterior-posterior; BMI, body mass index; CEA, centre edge angle; FABER, flexion abduction and internal rotation; FADIR, flexion adduction and internal rotation; FAIS, femoroacetabular impingement syndrome; NR, not reported; OA osteoarthritis; ROM, range of motion; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; α, alpha angle.

Table 2 Summary of included intervention studies

Author, year	FAIS group: FAIS type	FAIS group: Criteria	FAIS group: Sample	Intervention	Follow-up period	Controls: Criteria	Controls: Sample	Comparability	Tasks	Reported differences in hip and pelvic kinematics and joint torques
Brisson *et al*, 2013[23]	Unilateral cam only FAIS	NR	n=10 7 men Age 29.9 (7.2)	Surgery (4 open, 6 combined)	Mean=21.1 (9.4) Range 10–32 months	NR	n=13 8 men Age 34.2 (9.9)	Age Sex BMI	Walking	**Pre-operative versus post-operative** No reported differences **Pre-operative versus controls** Patients with FAIS walked with: ▶ Less total frontal plane ROM
Lamontagne *et al*, 2011[35]	Unilateral cam only FAIS	▶ Aged 18–50 years old ▶ Positive impingement test ▶ Unilateral hip pain ▶ No signs of OA, combined FAIS or pincer ▶ α>50° (AP and Dunne X-ray)	n=10 7 men Age 29 (7.2)	Surgery (open and combined)	Range 8–32 months	–	–	–	Walking	**Pre-operative versus post-operative** No reported differences
Rylander *et al*, 2013[12]	Cam, pincer and combined FAIS	▶ Positive impingement and labral stress test ▶ No other lower limb, spine or back problems ▶ α>54° (MRI, cross-table lateral and AP X-ray) OR ▶ CEA>35° (MRI, cross-table lateral and AP X-ray)	n=17 12 men Age 35.4 (8.9)	Surgery (labrectomy or labral repair; +/– microfracture)	12 months	▶ Self-reported lack of hip pain ▶ No lower limb injury history	n=17 12 men Age 34.9 (9.7)	Age Sex BMI	Walking Stairs	**Pre-operative versus post-operative** *Walk*: Post-operatively participants walked with: ▶ Greater hip sagittal and transverse plane ROM and greater peak hip flexion, and internal rotation angle *Stairs*: No reported differences **Pre-operative versus controls** *Walk:* FAIS group walked with: ▶ Less total sagittal, frontal and transverse plane ROM ▶ Smaller peak hip flexion, abduction and IR angle *Stairs:* FAIS group ascended stairs with: ▶ Less total sagittal plane ROM ▶ Smaller peak hip extension and IR angle ▶ Larger peak pelvic tilt ▶ Larger total pelvic rotation ROM

Age reported as means (SD).
AP, anterior-posterior; BMI, body mass index; CEA, centre edge angle; FAIS, femoroacetabular impingement syndrome; IR, internal rotation; NR, not reported; OA osteoarthritis; ROM, range of motion; α, alpha angle.

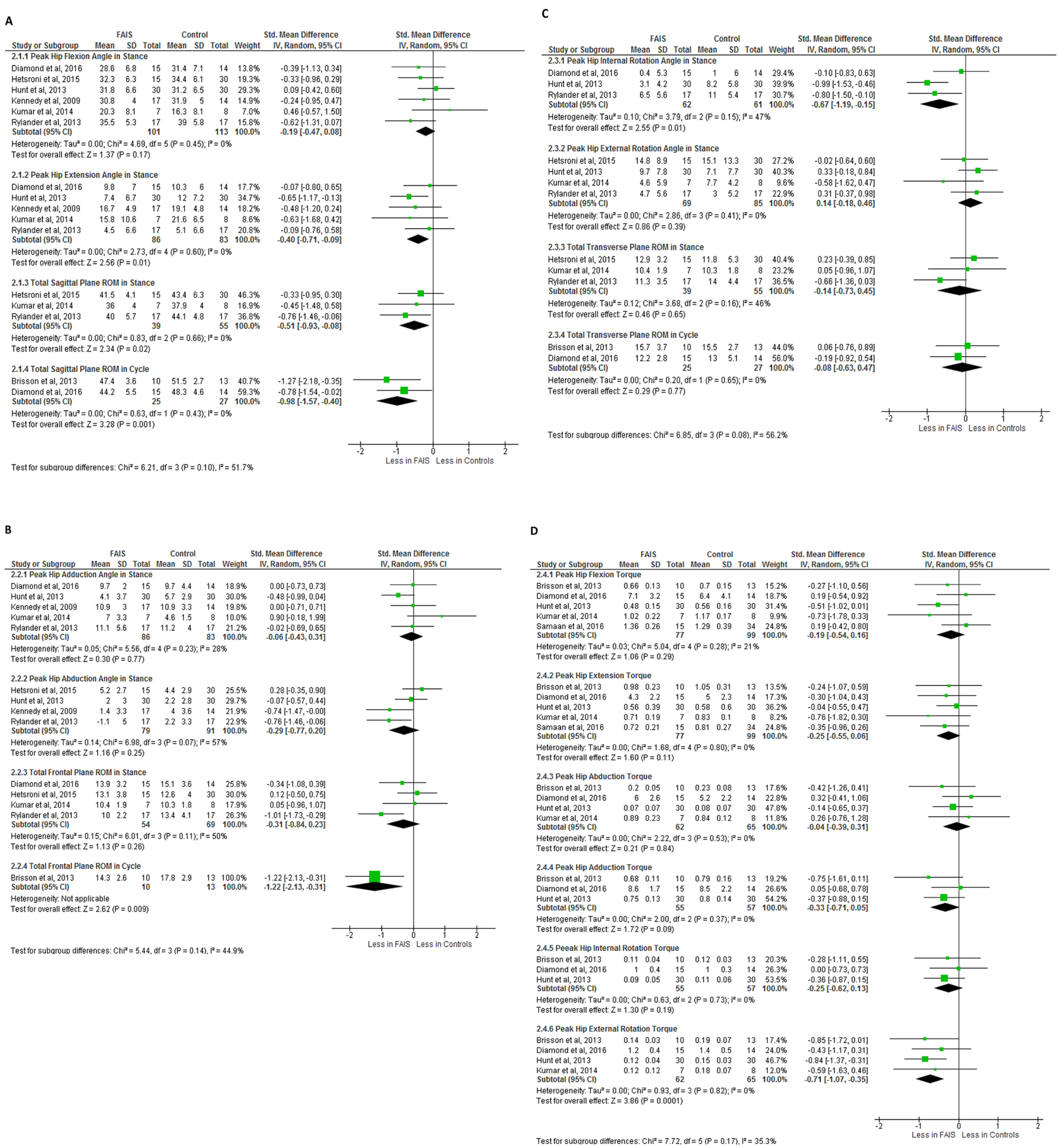

Figure 2 (A) Meta-analysis of sagittal plane hip kinematics. (B) Meta-analysis of frontal plane hip kinematics. (C) Meta-analysis of transverse plane hip kinematics. (D) Meta-analysis of external joint torques; during walking. FAIS, femoroacetabular impingement syndrome; ROM, range of motion.

(figure 2C) but no difference in peak hip external rotation angle (0.14, 95% CI –0.18 to 0.46; I^2=0%, P=0.41)[12 26–28] and total transverse plane ROM (−0.14, 95% CI −0.73 to 0.45; I^2=46%, P=0.16)[12 26 28] during stance in patients with FAIS compared with controls (figure 2C). Total transverse plane ROM in a full walking cycle was reported in two studies, with pooled data showing limited evidence of no difference between groups (−0.08, 95% CI −0.63 to 0.47; I^2=0%, P=0.65)[23 25] (figure 2C).

Qualitative synthesis of unpooled studies

Two studies, with similar samples,[23 24] reported peak hip internal and external rotation angles in a full walking cycle. The study with the larger sample reported no difference in peak internal and external rotation angles.[24] Diamond *et al*[25] found no between-group differences (0.02, 95% CI −0.71 to 0.75) in peak hip external rotation angle in swing (table 3).

Walking pelvic kinematics: FAIS versus controls

Due to the variability in collection and inconsistencies of reporting pelvic kinematics, qualitative synthesis was performed on information regarding pelvic kinematics.

Sagittal plane pelvic kinematics: FAIS versus controls

One low-quality[26] study and one moderate-quality[12] study described limited evidence of no difference in peak anterior pelvic tilt angle during stance (0.16, 95% CI −0.78 to 0.46; 0.12, 95% CI −0.55 to 0.80, respectively) (table 4).One low-quality study[26] found that patients with FAIS had a greater

Table 3 Hip kinematics, FAIS versus controls

		Sagittal plane								
		Peak hip flexion angle			Peak hip extension angle			Total sagittal plane ROM		
Activity	Author	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)
Walking	Brisson *et al*[23]*	32.2 ± 4.1 °†	32.8±4.3°†	−0.14 (−0.96 to 0.69)	15.2±3.1°†	18.7±4.3°†	−0.88 (−1.75 to −0.01)	47.4±3.6°†	51.5±2.7°†	−1.27 (−2.18 to −0.35)
	Diamond *et al*[25]	28.6 ± 6.8 °	31.4±7.1°	−0.39 (−1.13 to 0.34)	9.8±7.0°‡	10.3±6.0°‡	−0.07 (−0.80 to 0.65)	44.2±5.5°†	48.3±4.6°†	−0.78 (−1.54 to −0.02)
	Hetsroni *et al*[26]	32.3 ± 6.3 °	34.4±6.1°	−0.33 (−0.96 to 0.29)	NR	NR	UTD	41.5±4.1°	43.4±6.3°	−0.33 (−0.95 to 0.03)
	Hunt *et al*[27]	31.8 ± 6.6 °	31.2±6.5°	0.09 (−0.42 to 0.60)	7.4±6.7°	12.0±7.2°	−0.65 (−1.17 to −0.13)	–	–	–
	Kennedy *et al*[24]	30.8 ± 4.0 °§	31.9±5.0°§	−0.24 (−0.95 to 0.47)	16.7±4.9°§	19.1±4.8°§	−0.48 (−1.20 to 0.24)	NR	NR	UTD
	Kumar *et al*[28]‡	20.3 ± 8.1 °	16.3±8.1°	−0.46 (−0.57 to 1.50)	15.8±10.6°	21.6±6.5°	−0.63 (−1.68 to 0.42)	36.0±4.0°	37.9±4.0°	−0.45 (−1.48 to 0.58)
	Rylander *et al*[12]	35.5 ± 5.3°	39±5.8°	−0.62 (−1.31 to 0.07)	4.5±6.6°	5.1±6.6°	−0.09 (−0.76 to 0.58)	40.0±5.7°	44.1±4.8°	−0.76 (−1.46 to −0.06)
Squat	Bagwell *et al*[30]	106.6 ± 14.0 °	113.0±6.7°	−0.62 (−1.36 to 0.11)	–	–	–	–	–	–
	Kumar *et al*[28]‡	81.9±8.9°	81.7±9.4°	0.02 (−0.99 to 1.03)	–	–	–	79.8±11.1°	74.2±6.8°	0.58 (−0.46 to 1.63)
	Lamontagne *et al*[31]	NR	NR	UTD	–	–	–	–	–	–
Stairs	Rylander *et al*[12]	66.3±5.9°	66.6±6.5°	−0.06 (−0.73 to 0.61)	−11.4±6.9°	−6.6±4.0°	−0.83 (−1.54 to −0.13)	54.8±3.7°	60.0±4.5°	−1.23 (−1.97 to −0.49)
	Hammond *et al*[33]	60.6±5.2°	59.8±4.9°	0.16 (−0.47 to 0.78)	−7.1±8.2°	−6.1±5.2°	−0.14 (−0.76 to 0.48)	52.5±4.9°	53.1±3.2°	−0.14 (−0.76 to 0.48)
Drop jump	Kumar *et al*[28]‡	80.0±9.9°	73.7±13.4°	0.94 (−0.14 to 2.03)	–	–	–	–	–	–

		Frontal plane								
		Peak hip adduction angle			Peak hip abduction angle			Total frontal plane ROM		
Activity	Author	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)
Walking	Brisson *et al*[23]*	11.2±3.4°†	11.6±2.4°†	−0.13 (−0.96 to 0.69)	3.1±3.1°†	6.2±3.2°†	−0.95 (−1.82 to −0.07)	14.3±2.6°†	17.8±2.9°†	−1.22 (−2.13 to −0.31)
	Diamond *et al*[25]	9.7±2.0°	9.7±4.4°	0.00 (−0.73 to 0.73)	5.1±3.0°¶	6.9±3.4°¶	−0.55 (−1.29 to 0.20)	13.9±3.2°‡	15.1±3.6°‡	−0.34 (−1.08 to 0.39)
	Hetsroni *et al*[26]	NR	NR	UTD	5.2±2.7°	4.4±2.9°	0.28 (−0.35 to 0.90)	13.1±3.8°	12.6±4.0°	0.12 (−0.50 to 0.75)
	Hunt *et al*[27]	4.1±3.7°	5.7±2.9°	−0.48 (−0.99 to 0.04)	2.0±3.0°	2.2±2.8°	−0.07 (−0.57 to 0.44)	–	–	–
	Kennedy *et al*[24]	10.9±3.0°§	10.9±3.3°§	0.00 (−0.71 to 0.71)	1.4±3.4°§	4.0±3.6°§	−0.74 (−1.47 to −0.00)	NR	NR	UTD
	Kumar *et al*[28]‡	7.0±3.3°	4.6±1.5°	0.90 (−0.18 to 1.99)	–	–	–	10.4±1.9°	10.3±1.8°	0.05 (−0.96 to 1.07)
	Rylander *et al*[12]	11.1±5.6°	11.2±4°	−0.02 (−0.69 to 0.65)	−1.1±5.0°	2.2±3.3°	−0.76 (−1.46 to 0.06)	10±2.2°	13.4±4.1°	−1.01 (−1.73 to −0.29)
Squat	Bagwell *et al*[30]	–	–	–	11.8±6.2°	11.9±6.8°	−0.01 (−0.73 to 0.70)	–	–	–
	Kumar *et al*[28]‡	–	–	–	12.4±6.5°	18.8±5.1°	−1.04 (−2.14 to 0.06)	10.0±4.1°	11.2±4.5°	−0.26 (−1.28 to 0.76)
	Lamontagne *et al*[31]	NR	NR	UTD	NR	NR	UTD	–	–	–
Stairs	Rylander *et al*[12]	15.1±7.9°	12.6±5.7°	0.35 (−0.32 to 1.30)	3.3±4.9°	4.1±4.2°	−0.17 (−0.84 to 0.50)	18.4±6.6°	16.7±7.1°	0.24 (−0.43 to 0.92)
	Hammond *et al*[33]	7.8±4.1°	10.6±5.5°	−0.57 (−1.20 to 0.07)	8.5±4.5°	7.7±4.1°	0.18 (−0.44 to 0.80)	16.3±7.0°	18.8±7.3°	0.34 (−0.97 to 0.28)
Drop jump	Kumar *et al*[28]‡	1.7±3.2°	5.6±3.5°	−1.09 (−2.20 to 0.02)	13.2±9.0°	14.8±5.8°	−0.20 (−1.22 to 0.82)	–	–	–

Continued

King MG, *et al*. *Br J Sports Med* 2018;**52**:566–580. doi:10.1136/bjsports-2017-097839

Table 3 Continued

		Transverse plane								
		Peak hip internal rotation angle			Peak hip external rotation angle			Total transverse plane ROM		
Activity	**Author**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**
Walking	Brisson *et al*[23]*	9.2±5.5°†	9.6±3.2°†	−0.09 (−0.91 to 0.74)	6.6±6.7°†	5.9±3.0°†	0.14 (−0.69 to 0.96)	15.7±3.7°†	15.5±2.7°†	0.06 (−0.76 to 0.89)
	Diamond *et al*[25]	0.4±5.3°	1.0±6.0°	−0.10 (−0.83 to 0.63)	11.3±4.8°¶	11.2±3.9°¶	0.02 (−0.71 to 0.75)	12.2±2.8°†	13.0±5.1°†	−0.19 (−0.92 to 0.54)
	Hetsroni *et al*[26]	NR	NR	UTD	14.8±8.9°	15.1±13.3°	−0.02 (−0.64 to 0.60)	12.9±3.2°	11.8±5.3°	−0.23 (−0.39 to 0.85)
	Hunt *et al* [27]	3.1±4.2°	8.2±5.8°	−0.99 (−1.53 to −0.46)	9.7±7.8°	7.1±7.7°	0.33 (−0.18 to 0.84)	–	–	–
	Kennedy *et al*[24]	NR	NR	UTD	NR	NR	UTD	NR	NR	UTD
	Kumar *et al* [28]‡	–	–	–	4.6±5.9°	7.1±4.2°	−0.58 (−1.62 to 0.47)	10.4±1.9°	10.3±1.8°	0.05 (−0.96 to 1.07)
	Rylander *et al*[12]	6.5±5.6°	11.0±5.4°	−0.88 (−1.50 to −0.10)	4.7±5.6°	3.0±5.2°	0.31 (−0.37 to 0.98)	11.3±3.5°	14±4.4°	−0.66 (−1.36 to 0.03)
Squat	Bagwell *et al*[30]	9.4±7.8°	15.2±9.5°	−0.65 (−1.39 to 0.09)	–	–	–	–	–	–
	Kumar *et al*[28]‡	2.8±4.7°	5.8±5.2°	−0.57 (−1.61 to 0.47)	–	–	–	11.7±5.7°	17.4±4.4°	−1.06 (−2.17 to 0.04)
	Lamontagne *et al*[31]	NR	NR	UTD	NR	NR	UTD	–	–	–
Stairs	Rylander *et al*[12]	7.1±6.4°	12.1±4.2°	−0.90 (−1.61 to −0.19)	6.6±4.6°	4.5±4.9°	0.43 (−0.25 to 1.11)	13.8±3.9°	16.6±5.1°	−0.60 (−1.29 to 0.09)
	Hammond *et al*[33]	–	–	–	–	–	–	–	–	–
Drop jump	Kumar *et al*[28]‡	−1.0± 3.9°	3.7±5.3°	−0.94 (−2.03 to 0.15)	11.7±4.1°	11.6±3.5°	0.02 (−0.99 to 1.04)	–	–	–

Data reported mean and SD during stance unless otherwise indicated.
*Smaller sample of previously published data.
†Data reported in cycle.
‡Data supplied by author.
§Data extracted from graphs.
¶Data reported in swing phase.
FAIS, femoroacetabular impingement syndrome; NR, not reported; ROM, range of motion; SMD, standardised mean difference; UTD, unable to determine; –, data not collected.

Table 4 Pelvic kinematics, FAIS versus controls

		Sagittal plane (tilt)								
		Peak anterior tilt angle			Peak posterior tilt angle			Total sagittal plane ROM		
Activity	**Author**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%**
Walking	Brisson *et al*[23]*	–	–	–	–	–	–	3.2± 0.9†	2.7± 0.6°†	0.65 (–0.20 to 1.50)
	Hetsroni *et al*[26]	10.8± 4.9°	11.6± 4.8°	–0.16 (–0.78 to 0.46)	–	–	–	3.1± 1.0°	2.4± 0.7°	0.85 (0.20 to 1.50)
	Kennedy *et al*[24]	NR	NR	UTD	NR	NR	UTD	NR	NR	UTD
	Rylander *et al*[12]	13.8± 5.1°	13.2± 4.3°	0.12 (–0.55 to 0.80)	–	–	–	–	–	–
Squat	Bagwell *et al*[30]	23.4± 11.2°‡	12.5± 17.1°‡	0.73 (–0.01 to 1.48)	–	–	–	–	–	–
	Lamontagne *et al*[31]	4.2± 12.6°§¶	-3.8± 8.7°§¶	0.70 (–0.11 to 1.50)	–	–	–	14.7± 8.4°	24.2± 6.8°	–1.18 (–2.04 to –0.33)
	Ng *et al*[32]	–	–	–	–	–	–	11.0±4.0°	15.0±7.0°	–0.68 (–1.40 to 0.05)
Stairs	Rylander *et al*[12]	20.8± 6.2°	14.3± 3.9°	1.23 (0.49 to 1.97)	–	–	–	–	–	–

		Frontal plane (obliquity)								
		Peak pelvic drop			Peak pelvic hike (rise)			Total frontal plane ROM		
Activity	**Author**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**
Walking	Brisson *et al*[23]*	–	–	–	–	–	–	10.8± 2.8°†	13.4± 3.2°†	–0.83 (–1.69 to 0.04)
	Hetsroni *et al*[26]	5.3± 1.9°	5.6± 2.4°	–0.31 (–0.93 to 0.32)	–	–	–	9.5± 3.4°	10.7± 3.7°	–0.33 (–0.95 to 0.30)
	Kennedy *et al*[24]	4.8± 4.7°§	6.6± 1.4°§	–0.48 (–1.20 to 0.23)	4.7± 4.4°§	5.7± 1.4°§	–0.29 (–1.00 to 0.43)	NR	NR	UTD
	Rylander *et al*[12]	–	–	–	–	–	–	–	–	–
Squat	Bagwell *et al*[30]	–	–	–	–	–	–	–	–	–
	Lamontagne *et al*[31]	–	–	–	–	–	–	–	–	–
	Ng *et al*[32]	–	–	–	–	–	–	–	–	–
Stairs	Rylander *et al*[12]	–	–	–	–	–	–	–	–	–

		Transverse plane								
		Peak pelvic internal rotation angle			Peak pelvic external rotation angle			Total transverse plane ROM		
Activity	**Author**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**	**FAIS**	**Controls**	**SMD (95%CI)**
Walking	Brisson *et al*[23]*	–	–	–	–	–	–	13.3± 4.0°†	16.1± 3.3°†	-0.75 (-1.60 to 0.11)
	Hetsroni *et al*[26]	5.0± 2.6°	6.5± 2.8°	–0.54 (–1.17 to 0.09)	–	–	–	12.4± 3.5°	12.5± 4.5°	–0.02 (–0.64 to 0.60)
	Kennedy *et al*[24]	NR	NR	UTD	NR	NR	UTD	NR	NR	UTD
	Rylander *et al*[12]	–	–	–	–	–	–	9.0± 3.1°	8.4± 2.7°	0.20 (–0.47 to 0.88)
Squat	Bagwell *et al*[30]	–	–	–	–	–	–	–	–	–
	Lamontagne *et al*[31]	–	–	–	–	–	–	–	–	–
	Ng *et al*[32]	–	–	–	–	–	–	–	–	–
Stairs	Rylander *et al*[12]	–	–	–	–	–	–	13.8± 6.3°	8.3± 4.9°	0.95 (0.24 to 1.67)

Data reported mean and SD during stance unless otherwise indicated, fontal plane peak values refer to motion of the contralateral side.
*Smaller sample of previously published data.
†Data reported in cycle.
‡Pelvis angle at peak hip flexion.
§Data extracted from a graph.
¶Data obtained at peak squat depth.
FAIS, femoroacetabular impingement syndrome; NR, not reported; ROM, range of motion; SMD, standardised mean difference; UTD, unable to determine; –, data not collected.

sagittal plane pelvic ROM in stance (0.85, 95% CI 0.20 to 1.50) and one moderate-quality study[24] found no difference in total sagittal ROM during a full walking cycle (table 4).

Frontal plane pelvic kinematics: FAIS versus controls

Frontal pelvic obliquity did not differ for pelvic drop (−0.31, 95% CI −0.93 to 0.32[26]; −0.48, 95% CI −1.20 to 0.23[24]) in one low-quality[26] study and one moderate[24]-quality study or pelvic hike (rise) (−0.29, 95% CI −1.00 to 0.43) (table 4) in one moderate-quality study during stance phase.[24] One low-quality study[26] found no difference in total ROM in stance (−0.33, 95% CI −0.95 to 0.30) (table 4), whereas Kennedy *et al*[24] reported that patients with FAIS walked with less total pelvic frontal plane ROM during a complete walking cycle.

Transverse plane pelvic kinematics: FAIS versus controls

Transverse plane pelvic kinematics was evaluated by one low-quality[26] and two moderate-quality studies,[12 24] and no studies reported any differences between groups. Specifically, no differences were reported for peak pelvic internal rotation angle in stance (−0.54, 95% CI −1.17 to 0.09)[26] (table 4), peak internal and external rotation angles during a full walking cycle,[24] total transverse plane ROM (−0.02, 95% CI −0.64 to 0.60; 0.20, 95% CI −0.47 to 0.88)[12 26] (table 4) and total transverse plane ROM during a full walking cycle.[24]

Walking joint torques: FAIS versus controls

Five included studies reported joint torque information on FAIS versus controls. One additional moderate-quality study reported no between-group differences, but provided no data.[24]

Pooled data from five studies[23 25 27–29] demonstrated moderate evidence of a moderate effect size for lower peak external rotation joint torque (−0.71, 95% CI −1.07 to −0.35; I^2=0%, P=0.82) (figure 2D) in patients with FAIS compared with controls. There was moderate evidence of no difference in peak hip torques for flexion (−0.19, 95% CI −0.54 to 0.16; I^2=21%, P=0.28), extension (−0.25, 95% CI −0.55 to 0.06; I^2=0%, P=0.80), abduction (−0.04, 95% CI −0.39 to 0.31; I^2=0%, P=0.53), adduction (−0.33, 95% CI −0.71 to 0.05; I^2=0%, P=0.37) and internal rotation (−0.25, 95% CI −0.62 to 0.13; I^2=0%, P=0.73) (figure 2D). Additionally, one moderate-quality[29] study showed insufficient evidence that patients with FAIS had a greater peak hip flexion torque impulse (0.89, 95% CI 0.25 to 1.52) and no difference in extension torque impulse (−0.49, 95% CI −1.11 to 0.12) (table 5).

Subgroup analysis: walking kinematics and joint torques: cam only versus controls

Subgroup analysis of joint kinematics and external joint torques in cam-only populations demonstrated limited evidence of no difference in peak hip extension angle (−0.53, 95% CI −1.12 to 0.06; I^2=0%, P=0.82), and insufficient evidence of no difference in sagittal plane ROM (−0.45, 95% CI −1.48 to 0.58) compared with controls in the stance phase of walking (online supplementary C). Peak hip internal rotation in stance was unable to be subgrouped due to lack of data and no additional subgroup analyses differed from the reported results of the review.

Sensitivity analysis: removal of data estimated from graphs

Sensitivity analyses were conducted where manually extracted data from published graphs were removed from the meta-analyses. Four sensitivity analyses were conducted with no noticeable changes in the reported results (online supplementary D).

Squat kinematics: FAIS versus controls

Squatting kinematics was investigated in four studies.[28 30–32] One study controlled squat height to a maximum depth of 25% of body height,[28] two studies controlled squat height to a maximum depth of 1/3 tibial tuberosity height[30 31] and one allowed maximum depth to be full range.[32] Pooled data of reported squat depths showed moderated evidence of a large effect that FAIS participants squatted to a lesser depth than controls (SMD 0.92, 95% CI 0.46 to 1.38; I^2=0%, P=0.77) (figure 3).

Due to the variability in outcomes reported, kinematic squat variables were qualitatively synthesised. Hip kinematics were investigated by three medium-quality studies[28 30 31] with no differences observed in all outcomes investigated. Specifically, no difference in peak hip angles in all three planes at maximum squat depth[31]; no difference in peak hip flexion, abduction and internal rotation angle between patients with FAIS and controls (flexion −0.62, 95% CI −1.36 to 0.11; abduction −0.01, 95% CI −0.73 to 0.70; internal rotation −0.65, 95% CI −1.39 to 0.09),[30] (flexion 0.02, 95% CI −0.99 to 1.03; abduction −1.04, 95% CI −2.14 to 0.06; internal rotation −0.57, 95% CI −1.61 to 0.47)[28]; and no difference in total ROM in all planes (sagittal 0.58, 95% CI −0.46 to 1.63; frontal −0.26, 95% CI −1.28 to 0.76; transverse −1.06, 95% CI −2.17 to 0.04)[28] (table 3).

Two medium-quality studies[30 31] demonstrated no difference in pelvic tilt at maximum squat depth (0.73, 95% CI −0.01 to 1.48[30]; 0.70, 95% CI −0.11 to 1.50)[31] (table 4). Total sagittal plane pelvic ROM was investigated in two moderate-quality studies[31 32] with conflicting results. Lamontagne *et al*[31] found patients with FAIS squatted with less total sagittal plane pelvic ROM (−1.18, 95% CI −2.04 to −0.33) whereas Ng *et al*[32] found no between-group differences (−0.68, 95% CI −1.40 to 0.05) (table 4).

Squat joint torques: FAIS versus controls

Qualitative synthesis of unpooled studies

Squat hip joint torques were investigated in two moderate-quality studies. Kumar *et al*[28] found that patients with FAIS squatted with less peak hip external rotation torque (SMD −0.13, 95% CI −0.21 to −0.05) but no difference in peak hip flexion (0.19, 95% CI −0.83 to 1.21), peak hip abduction (0.00, 95% CI −1.01 to 1.01) or peak internal rotation (−0.34, 95% CI −1.37 to 0.69) (table 5) joint torque. Bagwell *et al*[30] found a lower mean hip flexion torque (−0.79, 95% CI −1.53 to −0.04), but no difference in mean hip abduction torque (0.20, 95% CI −0.51 to 0.92) and mean hip internal rotation torque (0.10, 95% CI −0.62 to 0.81) in patients with FAIS compared with controls.

Drop landing kinematics and joint torques: FAIS versus controls

Drop landing kinematics and joint torques were investigated in one moderate quality study,[28] finding insufficient evidence of no difference in all hip kinematics and joint torque outcomes (table 3 and 5).

Stairs kinematics and joint torques: FAIS versus controls

Qualitative synthesis of unpooled studies

Stair ascent kinematics was investigated in one medium-quality[12] study and one low-quality[33] study with conflicting results. Hammond *et al*[33] found no difference in hip kinematics (table 3) whereas Rylander *et al*[12] found patients with FAIS demonstrated a smaller peak hip extension angle (−0.83, 95% CI −1.54 to

Table 5 External joint torques, FAIS versus controls

		Sagittal plane					
		Peak hip flexion torque			Peak hip extension torque		
Activity	Author	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)
Walking	Brisson *et al*[23]*	0.66±0.13	0.70±0.15	−0.27 (−1.10 to 0.56)	0.98±0.23	1.05±0.31	−0.24 (−1.07 to 0.59)
	Diamond *et al*[25]	7.10±3.2	6.40±4.1	0.19 (−0.54 to 0.92)	4.30±2.20	5.00±2.30	−0.30 (−1.04 to 0.43)
	Hunt *et al*[27]	0.48±0.15	0.56±0.16	−0.51 (−1.02 to 0.01)	0.56±0.39	0.58±0.60	−0.04 (−0.55 to 0.47)
	Kennedy *et al*[24]	NR	NR	UTD	NR	NR	UTD
	Kumar *et al*[28]*†	1.02±0.22	1.17±0.17	0.73 (−1.78 to 0.33)	0.71±0.19	0.83±0.10	−0.76 (−1.82 to 0.30)
	Samaan *et al*[29]	1.36±0.26	1.29±0.39	0.19 (−0.42 to 0.80)	0.72±0.21	0.81±0.27	−0.35 (−0.96 to 0.26)
	Samaan *et al*[29]	0.14±0.04‡	0.11±0.03‡	0.89 (0.25 to 1.52)	0.10±0.04‡	0.12±0.04‡	−0.49 (−1.11 to 0.12)
Squat	Bagwell *et al*[30]*	0.45±0.15§	0.56±0.12§	−0.79 (−1.53 to −0.04)	–	–	–
	Kumar *et al*[28]*†	0.65±0.29	0.60±0.20	0.19 (−0.83 to 1.21)	–	–	–
Stairs	Hammond *et al*[33]	0.97±0.36	0.70±0.19	0.92 (0.26 to 1.57)	0.15±0.07	0.14±0.09	0.12 (−0.50 to 0.74)
Drop jump	Kumar *et al*[28]*†	1.38±0.51	1.47±0.38	−0.19 (−1.21 to 0.83)	1.50±0.81	1.79±0.52	−0.41 (−1.44 to 0.62)
Sit-to-stand	Samaan *et al*[34]	0.85±0.19	0.86±0.26	−0.04 (−0.63 to 0.55)	–	–	–
		Frontal plane					
		Peak hip abduction torque			Peak hip adduction torque		
Activity	Author	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)
Walking	Brisson *et al*[23]*	0.20±0.05	0.23±0.08	−0.42 (−1.26 to 0.41)	0.68±0.11	0.79±0.16	−0.75 (−1.61 to 0.11)
	Diamond *et al*[25]	6.00±2.60	5.20±2.20	0.32(−0.41 to 1.06)	8.60±1.70	8.50±2.20	0.05 (−0.68 to 0.78)
	Hunt *et al*[27]	0.07±0.07	0.08±0.07	−0.14 (−0.65 to 0.37)	0.75±0.13	0.80±0.14	−0.37 (−0.88 to 0.15)
	Kennedy *et al*[24]	NR	NR	UTD	NR	NR	UTD
	Kumar *et al*[28]*†	0.89±0.23	0.84±0.12	0.26 (−0.76 to 1.28)	–	–	–
	Samaan *et al*[29]	–	–	–	–	–	–
	Samaan *et al*[29]	–	–	–	–	–	–
Squat	Bagwell *et al*[30]*	0.12±0.11§	0.09±0.17§	0.20 (−0.51 to 0.92)	–	–	–
	Kumar *et al*[28]*†	0.29±0.16	0.29±0.11	0.00 (−1.01 to 1.01)	–	–	–
Stairs	Hammond *et al*[33]	–	–	–	0.79±0.12	0.85±0.12	−0.49 (−1.12 to 0.14)
Drop jump	Kumar *et al*[28]*†	0.37±0.28	0.45±0.45	−0.20 (−1.22 to 0.82)	0.32±0.09	0.20±0.24	0.61 (−0.44 to 1.65)
Sit-to-stand	Samaan *et al*[34]	–	–	–	–	–	–

Continued

Table 5 Continued

		Transverse plane					
		Peak hip external rotation torque			Peak hip internal rotation torque		
Activity	Author	FAIS	Controls	SMD (95%CI)	FAIS	Controls	SMD (95%CI)
Walking	Brisson *et al*[23]*	0.14±0.03	0.19±0.07	−0.85 (−1.72 to 0.01)	0.11±0.04	0.12±0.03	−0.28 (−1.11 to 0.55)
	Diamond *et al*[25]	1.20±0.40	1.40±0.50	−0.43 (−1.17 to 0.31)	1.00±0.40	1.00±0.30	0.00 (−0.73 to 0.73)
	Hunt *et al*[27]	0.12±0.04	0.15±0.03	−0.84 (−1.37 to −0.31)	0.09±0.05	0.11±0.06	−0.36 (−0.87 to 0.15)
	Kennedy *et al*[24]	NR	NR	UTD	NR	NR	UTD
	Kumar *et al*[28]*†	0.12±0.12	0.18±0.07	−0.59 (−1.63 to 0.46)	–	–	–
	Samaan *et al*[29]	–	–	–	–	–	–
	Samaan *et al*[29]	–	–	–	–	–	–
Squat	Bagwell *et al*[30]*	–	–	–	0.06±0.10§	0.05±0.10§	0.10 (−0.62 to 0.81)
	Kumar *et al*[28]*†	−0.09±0.11	0.04±0.02	−0.13 (−0.21 to −0.05)	0.11±0.03	0.14±0.04	−0.34 (−1.37 to 0.69)
Stairs	Hammond *et al*[33]	–	–	–	–	–	–
Drop jump	Kumar *et al**‡ [28]	–	–	–	0.24±0.14	0.33±0.19	−0.50 (−1.54 to 0.53)
Sit-to-stand	Samaan *et al*[34]	–	–	–	–	–	–

Data reported as peaks in mean and SD during stance unless otherwise indicated.
*Internal joint torque converted to external joint torque.
†Data supplied by author.
‡Data reported as impulse.
§Data reported as means.
FAIS, femoroacetabular impingement syndrome; NR, not reported; SMD, standardised mean difference; UTD, unable to determine; –, data not collected.

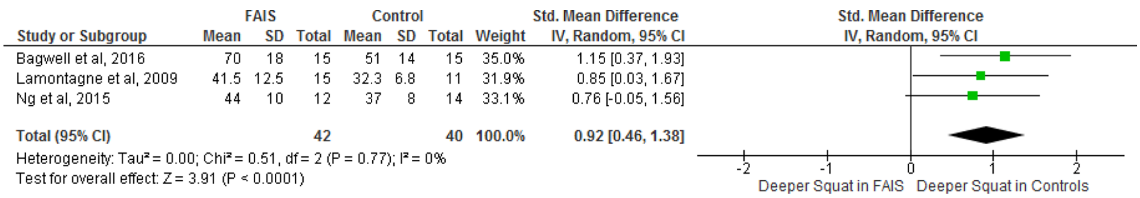

Figure 3 Meta-analysis of squat depth, FAIS versus controls. FAIS, femoroacetabular impingement syndrome.

−0.13), total hip sagittal plane ROM (−1.23, 95% CI −1.97 to −0.49) and peak hip internal rotation angle (−0.90, 95% CI −1.61 to −0.19) (table 3) compared with controls. Rylander *et al*[12] also found that patients with FAIS had greater total pelvic rotation ROM (0.95, 95% CI 0.24 to 1.67) and anterior pelvic tilt (1.23, 95% CI 0.49 to 1.97) (table 4) compared with controls. One low-quality study[33] investigated hip joint torques during stair ascent. The results show insufficient evidence that patients with FAIS ascend stairs with a greater peak hip flexion joint torque (0.92, 95% CI 0.26 to 1.57) and no difference in peak hip extension and peak hip adduction torque (table 5).

Sit-to-stand joint torques: FAIS versus controls

Qualitative synthesis of unpooled studies

Peak hip flexion joint torque was investigated in one moderate-quality study[34] finding insufficient evidence of no difference in peak hip joint torque (−0.04, 95% CI −0.63 to 0.55) (table 5) between groups.

Secondary outcome preintervention versus postintervention

Qualitative synthesis of unpooled studies

Three included studies (one moderate[12] and two low quality[23 35]) investigated the effects of arthroscopic surgery on kinematics and joint torques in walking,[12 23] squatting[35] and ascending stairs[12] (table 2). One study reported insufficient evidence of improvements in sagittal plane hip ROM, peak hip flexion angle, peak hip internal rotation angle and hip transverse plane ROM during stance phase of walking, following arthroscopic surgery.[12] Another reported insufficient evidence of no differences during a full walking cycle following surgery.[23] During a stair ascent, Rylander *et al*[12] found there was insufficient evidence of no change in hip and pelvic kinematics following arthroscopic surgery. During squatting, the postoperative participants with FAIS squatted to a lower depth with no difference in peak hip flexion angle.[35]

DISCUSSION

Movement patterns of patients with FAIS were different from controls. Specifically, patients with FAIS had lower peak hip extension, total sagittal plane ROM and peak hip internal rotation during stance phase of walking and squatted to a lesser depth, with no difference in hip flexion range. The pooled results of hip kinematic differences during walking build on the results of the previous review,[11] but few conclusions can be made for the other tasks, and for pelvic kinematics. These represent areas of future research.

Reduced hip extension towards terminal stance is consistent with findings in early-stage hip OA,[36] end-stage hip OA[37] and following total hip replacement.[38] Reduced hip extension may be a strategy to reduce load on the anterior hip during walking.[39] However, this behaviour has also been hypothesised to be maladaptive, decreasing the stimulus to anterior hip musculature, which can negatively affect hip stability over time.[40 41] At this time, the implications of lower peak hip extension angle during walking are not known.

Patients with FAIS produced lower peak external rotation torque, and lower peak hip internal rotation angles during walking compared with controls. These adaptations may represent a strategy to avoid positions of internal rotation, which are often reported to be painful in patients with FAIS.[5] As external moments are offset by internal moments of the antagonistic muscle groups/movements, a lower peak external rotation joint torque may decrease the demand on the internal rotators to minimise pain/discomfort.[27]

The effect size was small for lower peak hip extension angle (−0.40), moderate for lower peak hip internal rotation angle (−0.67) and moderate for lower peak hip external rotation torque (−0.71). The clinical implications of these differences and the long-term effects of alterations in biomechanics on joint health and long-term outcomes in patients with FAIS are relatively unknown, as no studies have evaluated these outcomes over time. Longitudinal studies into whether these differences in walking are associated with symptom or disease progression are needed to understand if such impairments may benefit from targeted management strategies, or whether they are protective movement patterns. Such information would enhance our understanding of the association between FAIS and OA.

Participants with FAIS did not squat as deep as controls, despite no difference in peak hip flexion angle. Reduced squat depth, but no difference in peak hip flexion angle may reflect poor motor programming, pain or fear of the task. Before recommendations can be made, greater investigations into the barriers to squat depth need to be explored. Since squatting type movements are required during everyday activities, patients with FAIS may benefit from skill retraining as a component of conservative management strategies.

There were insufficient studies to draw conclusions for clinical practice on tasks such as stair ascent, sit-to-stand and drop landing tasks. We recommend that further research be conducted into these and more complex activities to provide better insight into movement strategies associated with FAIS and whether targeting these differences could provide benefit in management strategies.

Over recent times there has been a rapid rise in the rates of arthroscopic surgery for FAIS.[13] However, only three included studies evaluated the effects of surgical interventions on lower limb biomechanics during walking, squatting and ascending stairs. The conflicting results for the effect of surgery during walking may be due to surgical technique used (arthroscopic[12] vs open/combined[23]), FAIS type (cam, pincer, combined cohort[12] vs cam[23]) or follow-up time (12 months[12] vs 10–32 months[23]). The results of the review indicate that surgical interventions may have no effect on hip kinematics during ascending stairs and squatting tasks. Further research, determining the effects of surgical intervention on biomechanics, is required to draw clinical conclusions. More stringent reporting of postoperative rehabilitation protocols is also required to better interpret results and draw recommendations.

The review demonstrates the absence of studies evaluating the effect of exercise or physiotherapy on biomechanics in patients with FAIS, which should be addressed in future studies.

Limitations

There are limitations present in the included studies and in this review that require acknowledgement. The review only included studies published in the English language, potentially missing important information from studies published in other languages. Full data extraction was only completed by one author (MGK), with a random sample of 50% of the data extracted checked by the second author (PRL). Risk of bias assessment could not be performed with the reporting appraisal tool used for this study. Instead, cut-off scores for high, moderate and low reporting quality were defined. It is possible that studies with good reporting scores also have a high risk of bias. For example, all of the included studies scored 'zero' for outlining assessment period and blinding observers, resulting in a risk of potential detection bias. Additionally, all studies scored 'zero' for their generalisability of the results to relevant populations, decreasing the confidence in the external validity of the data presented. All of the included studies were case series or case–control, cross-sectional studies of low to moderate reporting quality and were included in the review regardless of their assessment, limiting the confidence in the findings of the review.[42] Additionally, due to the differing units in joint torque data, and the kinematic models used, absolute differences were not determined at this time, and thus SMDs were used to calculate between-group differences in the outcomes of the included studies. The SMD provides an indication of the magnitude of the between-group difference enabling an interpretation of the pooled analyses beyond statistical significance.

There were differences in the kinematic models used in the included studies with six using a modified Helen Hayes marker set,[23 24 27 31 32 35] seven using a segmented model[12 25 28–30 33 34] and an Oxford foot model with plug-in gait.[26] Sagittal plane kinematics is the most reliable output for three-dimensional motion capture models (with the exception of pelvic tilt), followed by frontal and then transverse plane.[43] Minimal detectable changes for three-dimensional motion capture analysis should be population specific[44] and have yet to be quantified in patients with FAIS. Additionally, SE of measurement (SEM) should be quantified on a per-model basis, only one included study provided SEM values associated with their analysis.[26] Due to under-reporting of data, temporal parameters of walking were not included in this review. There is an association between walking speed and hip joint kinematics and joint torques,[45] which would need to be considered in future studies.

A variety of diagnostic criteria were used for the radiographic definition of FAIS with minimal alpha angles ranging from 50° to 60° and CEA from 35° to 39°. This inconsistency may have created variability in the included study results and altered the likelihood of between-group effects. The studies included in the review do not allow for the determination of cause or effect. Whether biomechanical variations occur early and cause FAIS, or FAIS causes these biomechanical variations, is unknown.

The majority of participants included were recruited from orthopaedic clinics, and hence may reflect more severe presentations than those in athletic teams or presenting to health or medical practitioner clinics. Future research should be conducted on athletic populations and involve sport-specific movements, such as running and cutting, to determine if more complex, higher impact activities present a problem for patients with FAIS. Women are also under-represented in the samples. Future studies could evaluate the association between FAIS and biomechanics in women, as smaller alpha angles and greater hip anteversion have been observed in women with hip and groin pain compared with men.[46]

What is already known?

Femoroacetabular impingement syndrome (FAIS) is associated with decreased quality of life and persistent symptoms, and is a risk factor for the development of hip osteoarthritis. Synthesised information on movement strategies in patients with FAIS is limited.

What are the new findings?

- There is moderate evidence that people with FAIS walk with a lower peak hip extension angle, peak hip internal rotation angle and external rotation joint torque, with no difference in peak hip flexion angle in stance.
- There is moderate evidence that people with FAIS are unable to squat as deep as controls; however, this is not due to a difference in hip flexion range of motion.

CONCLUSION

The systematic review identified 11 cross-sectional and three pre-post intervention studies of low to moderate reporting quality. Based on pooled data of 11 studies, we found patients with FAIS exhibit alterations in hip movement strategies in activities such as walking and squatting, with insufficient evidence to draw significant clinical conclusions in tasks such as stair ascent, sit-to-stand and drop landings. The review found small to moderate alterations in hip movement strategies such as lower peak hip extension, peak internal rotation angle and peak external rotation joint torque during walking as well as a reduced squat depth in patients with FAIS compared with controls.

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REFERENCES

1 Griffin DR, Dickenson EJ, O'Donnell J, *et al*. The Warwick Agreement on femoroacetabular impingement syndrome (FAI syndrome): an international consensus statement. *Br J Sports Med* 2016;50:1169–76.
2 Martin RL, Enseki KR, Draovitch P, *et al*. Acetabular labral tears of the hip: examination and diagnostic challenges. *J Orthop Sports Phys Ther* 2006;36:503–15.
3 Groh MM, Herrera J. A comprehensive review of hip labral tears. *Curr Rev Musculoskelet Med* 2009;2:105–17.
4 Agricola R, Waarsing JH, Arden NK, *et al*. Cam impingement of the hip: a risk factor for hip osteoarthritis. *Nat Rev Rheumatol* 2013;9:630–4.
5 Byrd JW. Femoroacetabular impingement in athletes: current concepts. *Am J Sports Med* 2014;42:737–51.
6 Agricola R, Heijboer MP, Bierma-Zeinstra SM, *et al*. Cam impingement causes osteoarthritis of the hip: a nationwide prospective cohort study (CHECK). *Ann Rheum Dis* 2013;72:918–23.
7 Johnson AC, Shaman MA, Ryan TG. Femoroacetabular impingement in former high-level youth soccer players. *Am J Sports Med* 2012;40:1342–6.

8 Agricola R, Bessems JH, Ginai AZ, *et al*. The development of Cam-type deformity in adolescent and young male soccer players. *Am J Sports Med* 2012;40:1099–106.
9 Siebenrock KA, Ferner F, Noble PC, *et al*. The cam-type deformity of the proximal femur arises in childhood in response to vigorous sporting activity. *Clin Orthop Relat Res* 2011;469:3229–40.
10 Lahner M, Walter PA, von Schulze Pellengahr C, *et al*. Comparative study of the femoroacetabular impingement (FAI) prevalence in male semiprofessional and amateur soccer players. *Arch Orthop Trauma Surg* 2014;134:1135–41.
11 Diamond LE, Dobson FL, Bennell KL, *et al*. Physical impairments and activity limitations in people with femoroacetabular impingement: a systematic review. *Br J Sports Med* 2015;49:230–42.
12 Rylander J, Shu B, Favre J, *et al*. Functional testing provides unique insights into the pathomechanics of femoroacetabular impingement and an objective basis for evaluating treatment outcome. *J Orthop Res* 2013;31:1461–8.
13 Reiman MP, Thorborg K, Hölmich P. Femoroacetabular impingement surgery is on the rise-but what is the next step? *J Orthop Sports Phys Ther* 2016;46:406–8.
14 Moher D, Liberati A, Tetzlaff J, *et al*. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Int J Surg* 2010;8:336–41.
15 Genaidy AM, Lemasters GK, Lockey J, *et al*. An epidemiological appraisal instrument - a tool for evaluation of epidemiological studies. *Ergonomics* 2007;50:920–60.
16 Nix SE, Vicenzino BT, Collins NJ, *et al*. Characteristics of foot structure and footwear associated with hallux valgus: a systematic review. *Osteoarthritis Cartilage* 2012;20:1059–74.
17 Cohen J. *Statisticcal power analysis for the behavioral sciences*. Hillsdale: England Lawrence Eribaum Associates, 1988.
18 Higgins JP, Thompson SG, Deeks JJ, *et al*. Measuring inconsistency in meta-analyses. *BMJ* 2003;327:557–60.
19 van Tulder M, Furlan A, Bombardier C, *et al*. Updated method guidelines for systematic reviews in the cochrane collaboration back review group. *Spine* 2003;28:1290–9.
20 Hart HF, Culvenor AG, Collins NJ, *et al*. Knee kinematics and joint moments during gait following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *BJSM online* 2015.
21 Freke MD, Kemp J, Svege I, *et al*. Physical impairments in symptomatic femoroacetabular impingement: a systematic review of the evidence. *Br J Sports Med* 2016;50:1180.
22 Rathleff MS, Rathleff CR, Crossley KM, *et al*. Is hip strength a risk factor for patellofemoral pain? A systematic review and meta-analysis. *Br J Sports Med* 2014;48:1088.
23 Brisson N, Lamontagne M, Kennedy MJ, *et al*. The effects of cam femoroacetabular impingement corrective surgery on lower-extremity gait biomechanics. *Gait Posture* 2013;37:258–63.
24 Kennedy MJ, Lamontagne M, Beaulé PE. Femoroacetabular impingement alters hip and pelvic biomechanics during gait Walking biomechanics of FAI. *Gait Posture* 2009;30:41–4.
25 Diamond LE, Wrigley TV, Bennell KL, *et al*. Hip joint biomechanics during gait in people with and without symptomatic femoroacetabular impingement. *Gait Posture* 2016;43:198–203.
26 Hetsroni I, Funk S, Ben-Sira D, *et al*. Femoroacetabular impingement syndrome is associated with alterations in hindfoot mechanics: A three-dimensional gait analysis study. *Clin Biomech* 2015;30:1189–93.
27 Hunt MA, Guenther JR, Gunether JR, *et al*. Kinematic and kinetic differences during walking in patients with and without symptomatic femoroacetabular impingement. *Clin Biomech* 2013;28:519–23.
28 Kumar D, Dillon A, Nardo L, *et al*. Differences in the association of hip cartilage lesions and cam-type femoroacetabular impingement with movement patterns: a preliminary study. *Pm R* 2014;6:681–9.
29 Samaan MA, Schwaiger BJ, Gallo MC, *et al*. Joint loading in the sagittal plane during gait is associated with hip joint abnormalities in patients with femoroacetabular impingement. *Am J Sports Med* 2017;45.
30 Bagwell JJ, Snibbe J, Gerhardt M, *et al*. Hip kinematics and kinetics in persons with and without cam femoroacetabular impingement during a deep squat task. *Clin Biomech* 2016;31:87–92.
31 Lamontagne M, Kennedy MJ, Beaulé PE. The effect of cam FAI on hip and pelvic motion during maximum squat. *Clin Orthop Relat Res* 2009467645–50.
32 Ng KC, Lamontagne M, Adamczyk AP, *et al*. Patient-specific anatomical and functional parameters provide new insights into the pathomechanism of cam FAI. *Clin Orthop Relat Res* 2015;473:1289–96.
33 Hammond CA, Hatfield GL, Gilbart MK, *et al*. Trunk and lower limb biomechanics during stair climbing in people with and without symptomatic femoroacetabular impingement. *Clin Biomech* 2017;42:108–14.
34 Samaan MA, Schwaiger BJ, Gallo MC, *et al*. Abnormal joint moment distributions and functional performance during sit-to-stand in femoroacetabular impingement patients. *Pm R* 2017;9:08:08.
35 Lamontagne M, Brisson N, Kennedy MJ, *et al*. Preoperative and postoperative lower-extremity joint and pelvic kinematics during maximal squatting of patients with cam femoro-acetabular impingement. *J Bone Joint Surg Am* 201193 Suppl 240–5.
36 Watelain E, Dujardin F, Babier F, *et al*. Pelvic and lower limb compensatory actions of subjects in an early stage of hip osteoarthritis. *Arch Phys Med Rehabil* 2001;82:1705–11.
37 Hurwitz DE, Hulet CH, Andriacchi TP, *et al*. Gait compensations in patients with osteoarthritis of the hip and their relationship to pain and passive hip motion. *J Orthop Res* 1997;15:629–35.
38 Beaulieu ML, Lamontagne M, Beaulé PE. Lower limb biomechanics during gait do not return to normal following total hip arthroplasty. *Gait Posture* 2010;32:269–73.
39 Lewis CL, Sahrmann SA, Moran DW. Effect of hip angle on anterior hip joint force during gait. *Gait Posture* 2010;32:603–7.
40 Semciw AI, Green RA, Murley GS, *et al*. Gluteus minimus: an intramuscular EMG investigation of anterior and posterior segments during gait. *Gait Posture* 2014;39:822–6.
41 Semciw AI, Pizzari T, Murley GS, *et al*. Gluteus medius: an intramuscular EMG investigation of anterior, middle and posterior segments during gait. *J Electromyogr Kinesiol* 2013;23:858–64.
42 Weir A, Rabia S, Ardern C. Trusting systematic reviews and meta-analyses: all that glitters is not gold!. *Br J Sports Med* 2016;50:1100–1.
43 McGinley JL, Baker R, Wolfe R, *et al*. The reliability of three-dimensional kinematic gait measurements: a systematic review. *Gait Posture* 2009;29:360–9.
44 Wilken JM, Rodriguez KM, Brawner M, *et al*. Reliability and Minimal Detectible Change values for gait kinematics and kinetics in healthy adults. *Gait Posture* 2012;35:301–7.
45 Lelas JL, Merriman GJ, Riley PO, *et al*. Predicting peak kinematic and kinetic parameters from gait speed. *Gait Posture* 2003;17:106–12.
46 Hetsroni I, Dela Torre K, Duke G, *et al*. Sex differences of hip morphology in young adults with hip pain and labral tears. *Arthroscopy* 2013;29:54–63.