Running mechanics after repeated sprints in femoroacetabular impingement syndrome, cam morphology, and controls

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Keywords: sprinting; hip pain; groin; loading; fatigue
Abstract

Background: Individuals with femoroacetabular impingement syndrome (FAIS) often report pain during sports involving repeated sprinting. It remains unclear how sports participation influences running biomechanics in individuals with FAIS.

Hypothesis: Changes in running biomechanics and/or isometric hip strength following repeated sprint exercise would be greatest in individuals with FAIS compared with asymptomatic individuals with (CAM) and without cam morphology (Control).

Study design: Controlled laboratory study.

Level of evidence: Level 3.

Methods: Three-dimensional hip biomechanics during maximal running (10m) and hip strength were measured in 49 recreationally active individuals (FAIS=15; CAM=16; Control=18) before and after repeated sprint exercise performed on a non-motorized treadmill (8-16x30m). Effects of group and time were assessed for biomechanics and strength variables with repeated-measures analyses of variance. Relationships between hip pain (Copenhagen Hip and Groin Outcome Score) and changes in hip moments and strength following repeated sprint exercise were determined using Spearman’s correlation coefficients (ρ).

Results: Running speed, hip flexion angles, hip flexion and extension moments, and hip strength in all muscle groups were significantly reduced from pre to post. No significant between-group differences were observed before or after repeated sprint exercise. No significant relationships (ρ=0.04-0.30) were observed between hip pain and changes in hip moments or strength in the FAIS group.

Conclusions: Changes in running biomechanics and strength after repeated sprint exercise did not differ between participants with FAIS and asymptomatic participants with and without cam morphology. Self-reported pain did not appear to influence biomechanics during running or strength following repeated sprint exercise in participants with FAIS.
**Clinical Relevance:** A short bout of repeated sprinting may not elicit changes in running biomechanics in FAIS beyond what occurs in those without symptoms. Longer duration activities or activities requiring greater hip flexion angles may better provoke pathology-related changes in running biomechanics in individuals with FAIS.
Introduction

Femoroacetabular impingement syndrome (FAIS) is a clinical condition associated with repetitive premature contact between the proximal femur and acetabulum (i.e. impingement), which may lead to hip and/or groin pain and early cartilage degeneration in young to middle-aged active adults. Asphericity of the femoral head-neck (cam morphology) is often reported as a cause of symptoms and soft tissue damage in individuals with FAIS. Nonetheless, the large incidence of cam morphology in asymptomatic individuals suggests pain and disability in those with FAIS may arise from a combination of abnormal morphology, altered movement patterns, and/or impaired muscle function. A direct comparison between individuals with FAIS and asymptomatic cam morphology is critical for understanding how pain and morphology independently influence hip joint mechanics.

Few studies compared hip joint mechanics between symptomatic and asymptomatic individuals with cam morphology and found no differences in hip angles or moments during deep squatting or cross-body lunging. However, the low physical demands of tasks evaluated may explain the low pain levels reported by those with FAIS during laboratory assessments. Thus, more demanding sport-specific tasks like running may be more likely to provoke pain and alter movement patterns in individuals with FAIS. However, only a single study has investigated running biomechanics in any facet.

Individuals with FAIS often report pain during sports involving repeated sprinting and cutting maneuvers. Pain provoked during these high demand and repetitive tasks likely relates to overloading and associated damage to cartilage and/or soft tissues. The insidious presentation of pain in FAIS suggests neuromuscular fatigue may play a role in symptom presentation. However, this hypothesis is yet to be tested.

Individuals with FAIS often present with lower hip strength compared to healthy controls and asymptomatic individuals with cam morphology. Thus, it is possible that
muscle weakness and task demands may prevent individuals with FAIS from avoiding pain-provoking positions of impingement (deep hip flexion combined with adduction and internal rotation).37,42 Since muscles are the main shock absorbers of the musculoskeletal system,35,40 reductions in their capacity to produce force (i.e. neuromuscular fatigue)12 can lead to increases in joint loading,4 which may further lead to hip pain. Repeated sprint exercise is a controlled approach to emulating the mechanical demands of high intensity sports in a laboratory setting and has been shown to induce large levels of fatigue in the hip musculature.13 Thus, investigating running biomechanics in FAIS under fatigued conditions could shed light on the link between sports participation and hip pain in FAIS.

The aims of this study were to (i) compare effects of repeated sprint exercise on hip biomechanics during maximal sprint acceleration running (i.e. accelerated sprints) and isometric hip strength between individuals with FAIS, asymptomatic cam morphology, and healthy controls, and (ii) evaluate relationships between self-reported pain and changes in hip moments and strength following repeated sprint exercise in FAIS. We hypothesized changes in running biomechanics and/or isometric hip strength following repeated sprint exercise would be greatest in the FAIS group, and within the FAIS group, people with more pain would exhibit greater reductions in hip moments and strength following repeated sprint exercise.

**Materials and Methods**

**Participants**

A statistical *a priori* power analysis15 was performed based on studies investigating hip biomechanics during cross-body lunging in individuals with FAIS (n=35)19 and running in individuals with patellofemoral pain (n=38)42. The two studies were chosen to represent the cohort19 and task42 of interest. Based on differences in sagittal plane hip moments during cross-body lunging between three groups19 and transverse plane hip kinematics during running between two groups42, effect sizes of 0.68 (F ratios) and 1.49 (Cohen’s *d*) were calculated.
From these results we determined that $8^{19}$ to $12^{42}$ participants were required in each group to reach this effect size (with a power of 0.80 and alpha level of 0.05).

Forty-nine recreationally active individuals aged between 18-45 years were recruited from the community to participate in this exploratory study. Participants were assigned to one of three groups (FAIS = 15; asymptomatic cam morphology (CAM) = 16; healthy control (Control) = 18) depending on hip and groin symptoms, results of a clinical examination performed by one of three registered physiotherapists, and imaging findings from magnetic resonance imaging (MRI).\textsuperscript{20} Participants were assigned to the FAIS group if they had a history of hip or groin pain for more than 3 months, positive clinical impingement test, and definitive signs of cam morphology on MRI (maximum alpha angle $>55^\circ$). The impingement test was deemed positive if a participant’s pain could be replicated during either forced deep hip flexion combined with adduction and internal rotation (i.e. FADIR)\textsuperscript{20,44} or forced hip flexion combined with abduction and external rotation (i.e. FABER).\textsuperscript{20,44} Participants with no history of hip or groin pain and no clinical signs of impingement were assigned to either CAM or Control groups if they had maximum alpha angles $>55^\circ$ or $\leq55^\circ$ on MRI,\textsuperscript{9,23} respectively (full details of MRI in Supplementary Methods). Individuals were excluded if not currently involved in moderate to vigorous exercise at least 3-times per week, had any medical or self-reported contraindications to performing strenuous exercise, had any lower limb musculoskeletal injury in the last six months (other than FAIS), and/or had previous surgery on the study hip. Participants were asked to refrain from strenuous lower limb exercise and alcohol consumption for 24-hours prior to testing. Ethical approval was obtained from the institutional Human Research Ethics Committee. Participants were informed of the procedures and provided written informed consent, consistent with the Declaration of Helsinki.
Data collection procedures

Participants attended one MRI session and one laboratory testing session. Upon arrival to the laboratory, participants completed a series of questionnaires (detailed below) and had their anthropometrics measured. Participants then performed a brief familiarization with a non-motorized treadmill (Woodway Curve 3.0, WOODWAY USA, Waukesha, USA). Subsequently, participants’ overground accelerated sprint running biomechanics and isometric strength were evaluated before and after a repeated sprint exercise protocol performed on the non-motorized treadmill.16

Patient reported outcomes

All participants completed questionnaires about their history of sports participation and a modified Tegner Activity Scale9 (0 = sick leave or disability, 10 = competitive sports). Participants in the FAIS group also completed the international Hip Outcome Tool (iHOT-33)32 and the Copenhagen Hip and Groin Outcome Score (HAGOS)43 (0 = extreme hip/groin problems, 100 = no hip/groin problems), validated questionnaires for assessment of hip health in the last month or last week, respectively. The “Function, sports and recreational activities” subscale of the HAGOS questionnaire, which has been independently validated43 and is commonly implemented in athletic cohorts,11 was used as an indicator of hip pain in the week prior to testing. Following each repeated sprint, participants in the FAIS group were asked to rate their hip pain using an 11-point numerical rating scale (NRS) ranging from 0 (no hip pain) to 10 (worst hip pain imaginable). Participants were encouraged to consider their hip pain and not muscle fatigue. To distinguish between self-reported hip pain in the last week evaluated using the HAGOS “Function, sports and recreational activities” subscale and self-reported hip pain during the repeated sprint exercise, we will henceforth refer to these measurements as HAGOS subscale and NRS scale, respectively.

[Insert Table 1 here]
Isometric strength testing

Maximal voluntary isometric contractions were performed using a custom-made device consisting of a uniaxial load cell attached to a metal frame rig before and after the repeated sprint exercise. Participants performed hip extension, flexion, abduction, adduction, and external and internal rotation (Table 1). The load cell was attached as close as possible to the indicated bony landmark while ensuring participant comfort. Load cell position was marked with a permanent marker on the participant’s skin to ensure consistent placement following repeated sprint exercise. Joint angles were set using a manual goniometer. Before the repeated sprint exercise, participants performed two submaximal contractions followed by two maximal contractions separated by a minimum of 30 s rest. Extra rest was given to participants if required to minimize the effects of fatigue. Following the repeated sprint exercise, two maximal contractions were performed with minimal rest between repetitions to minimize recovery from the fatiguing task.

Repeated sprint exercise protocol

After a 1-minute self-selected submaximal running warm-up, participants performed a minimum of five 30 m sprints (70% to 100% of perceived maximal speed). Extra familiarization sprints were performed at participant request. Following strength testing, participants were equipped with a full-body reflective marker-set (61 markers) prior to performing a bout of repeated sprint exercise (described in detail elsewhere). The exercise consisted of 12x30 m sprints on a non-motorized treadmill. Following the 12th repeated sprint, participants who showed less than 8% decrease in maximal sprint speed were required to perform extra sprints until their maximal speed dropped to at least 8% of their initial speed. This threshold was implemented to limit between-participant variability and to recreate the highest demands observed in field and court sports. Before and after each treadmill sprint, three-dimensional marker positions and ground reaction forces (GRF) were collected during
10 m overground maximal running and two side-step cutting tasks (one cut for each side) (see Supplementary Figure 1). Testing between treadmill sprints lasted approximately 60 s with 15 s active slow jogging between trials. The most symptomatic leg was tested for participants in the FAIS group. An arbitrarily chosen leg with alpha angle above and below 55° was tested for participants in the CAM and Control groups, respectively. Hip biomechanics were computed for the running trials directly before (pre) and after (post) the repeated sprint exercise protocol.

Data processing

All data were recorded using Vicon Nexus 2.7.1 software (Vicon, Oxford Metrics Group, UK) at 2000 Hz (GRF and isometric force data) or 200 Hz (marker coordinates) (full details of Data processing in Supplementary Methods). All data was processed using MATLAB R2018b (MathWorks, MASS, USA). Maximum force value per task, per participant, per time point were converted to torque (N·m) (Table 1). Marker coordinates and GRF data were processed using MOtoNMS (version 2.2) toolbox for subsequent use in OpenSim (version 3.3). For each participant, a generic full-body model was linearly scaled to match individual anthropometry and used to determine hip sagittal, frontal, and transverse plane kinematics and internal moments using the inverse kinematics and inverse dynamics OpenSim tools, respectively. Joint moments were normalized to body mass (Nm·kg⁻¹). Gait events were visually inspected to identify foot-contact and toe-off events based on foot marker positions and vertical ground reaction forces. Stride cycles were manually cropped between consecutive ipsilateral toe-off events. Joint kinematics and moments were time-normalized to the duration of the stride cycle (%). Maximal running speed (m·s⁻¹), acceleration (m·s⁻²), stride length (m), stride time (s), stride frequency (Hz), contact time (s) were calculated to represent spatiotemporal parameters during running. The trial showing maximal speed from the two baseline trials (pre) and the last performed trial (post) per participant were used for analysis. Pre to post percentage differences in spatiotemporal and torque data were calculated as a mean
difference \((MD=(post-pre)/pre\times 100)\). Given the small magnitude of the hip angles and moments in the frontal and transverse planes, pre to post changes in hip angle and moments were calculated in raw units (post – pre).

**Statistical analysis**

Following inspecting data for normality, we used a two-way repeated measures analysis of variance (ANOVA) to analyze the interactions and main effects of group (FAIS, CAM, Control) and/or time (pre, post) on each spatiotemporal and strength measures (full details of *Statistical analysis* in Supplementary Methods). When a significant interaction or main effect was observed, post-hoc comparisons were performed with a Bonferroni correction for multiple comparisons to reduce the chance of Type-I error.\(^{45}\) A two-way repeated measures ANOVA was performed to assess differences between groups and time points for hip angles and moments using statistical parametric mapping.\(^ {34}\) Bonferroni post-hoc pairwise comparisons were performed if significant interactions between group and time were found. Spearman’s rank correlation coefficients (\(\rho\)) were used to evaluate the relationships between hip pain in the week prior testing (HAGOS subscale scores) and (i) changes in maximal running speed, (ii) changes in peak hip moments during running, and (iii) changes in isometric hip strength, in the FAIS group only. Statistical analyses were performed using MATLAB R2018b and RStudio (version 1.2.5, Boston, US). Significance was accepted for \(P<0.05\).

**Results**

**Participant characteristics**

Participant descriptive data are presented in Table 2. There were more males in the FAIS and CAM groups than in the Control group. No significant between-group differences were observed in weight, height, body mass index (BMI), lateral center edge angle, or activity level (minutes per week or Tegner scores). Both CAM and Control groups were significantly
younger than the FAIS group (P<0.008). Maximum alpha angle did not differ between FAIS and CAM groups but both were significantly higher than the Control group (P<0.001).

[Insert Table 2 here]

Spatiotemporal parameters

Spatiotemporal parameters are presented in Table 3. There were no significant differences in the number of sprints performed by participants in the FAIS (range: 9-15), CAM (8 to 14), and Control (8 to 16) groups. We observed no differences in maximal speed, maximal acceleration, step time, contact time, step length, or step frequency between FAIS, CAM, and Control groups at pre or post time points. Following repeated sprint exercise, maximal running speed (MD = -14 to -22%, P<0.001), maximal acceleration (MD = -13 to -18%, P<0.001), and step frequency (MD = -10 to -19%, P<0.001) significantly decreased and step time (MD = 12 to 25%, P<0.001) and contact time (MD = 19 to 28%, P<0.001) significantly increased in all groups.

[Insert Table 3 here]

Hip angles and moments

No significant group-time interactions were observed for hip angles (Figure 1) or moments (Figure 2) in any plane of movement. Main effects of time revealed a reduction, from pre to post, in hip flexion angles from mid-swing to early stance (see Supplementary Figure 2). Similarly, hip flexion and extension moments decreased from pre to post, primarily at the beginning and end of swing (see Supplementary Figure 3).

Isometric hip strength

No significant group-time interactions or main effects of group were observed for any strength task. However, we observed a main effect of time for all strength tasks suggesting a decrease in strength during hip extension (MD = -15 to -17%, P<0.001), flexion (MD = -17 to -29%, P<0.001), abduction (MD = -13 to -19%, P<0.001), adduction (MD = -7 to -19%, P<0.001),
external rotation (MD = -5 to -11%, P<0.001), and internal rotation (MD = -2 to -7 %, P=0.01) following repeated sprint exercise (Figure 3).

_HAGOS subscale and NRS pain scores_

In the FAIS group, 77% of participants reported difficulty running, and 85% reported difficulty performing explosive movements involving accelerations or decelerations on the HAGOS subscale, and 27% reported an increase in pain (NRS scale) following the repeated sprint exercise. No significant differences in pain scores (NRS scale) were observed between pre and post at the group level (median pain (range); pre = 0 (0-3), post = 0 (0-8), P=0.81).

_Relationship between pain and changes in maximal running speed, hip moments, and isometric hip strength in FAIS group_

No significant relationship was observed between hip pain scores in the week prior testing (HAGOS scale) and changes in maximal running speed ($\rho=0.19$, $P=0.49$). No significant relationships were observed between HAGOS subscale scores and changes in peak hip extension ($\rho=0.23$, $P=0.44$), flexion ($\rho=0.24$, $P=0.41$), or abduction ($\rho=0.04$, $P=0.89$) moments during running (see Supplementary Figure 4, top row). No significant relationships were observed between HAGOS subscale scores and changes in hip extension ($\rho=0.30$, $P=0.28$), flexion ($\rho=0.16$, $P=0.57$), or abduction ($\rho=0.30$, $P=0.28$) isometric strength following repeated sprint exercise (see Supplementary Figure 4, bottom row).

[Insert Figures 1-3 here]

**Discussion**

This study compared hip biomechanics during running (accelerated sprints) and isometric hip strength following repeated sprint exercise between individuals with FAIS, asymptomatic cam morphology, and activity matched healthy controls without cam morphology. The repeated sprint exercise resulted in significant reductions in maximal running speed, three-dimensional hip angles and moments during running, and isometric hip strength measures for all three
groups. In contrast to our hypotheses, we did not observe any between-group differences in running biomechanics or hip strength, either before or after repeated sprint exercise. In the FAIS group, a history of self-reported pain in the week prior to testing (HAGOS subscale) did not appear to influence hip biomechanics during running or hip strength following repeated sprint exercise. This novel observation highlights a discord between pain presentation and hip function during running in those with FAIS and warrants exploration in future studies.

**Effect of group and repeated sprint exercise on running biomechanics**

Consistent with the observed reductions in maximal running speed following repeated sprint exercise (14% to 22%), we observed decreased hip angles and moments after repeated sprint exercise compared to baseline in all three groups with no between-group differences. Decreases in hip flexion and extension moments were observed mainly during the swing phase, in agreement with previous findings of reduced hip moments and hip muscle activity following repeated sprints, only during swing. Although our results suggest hip moments during running in individuals with FAIS are comparable to asymptomatic individuals, regardless of the presence of cam morphology, our analysis does not account for muscle co-contraction or non-linear musculotendon dynamics that influence internal hip loading. Thus, future investigations of internal hip loading (e.g. hip contact forces) during running in FAIS and any fatigue-related effects are warranted.

**Effect of group and repeated sprint exercise on isometric hip strength**

Consistent with Brunner et al., we observed no significant between-group differences in isometric hip strength at baseline. We also observed significant reductions in isometric hip strength (up to 34%) following repeated sprint exercise with no between-group differences, suggesting all groups likely experienced similar levels of fatigue. Our results contrast previous reports of lower hip strength in FAIS compared to asymptomatic controls. Prior studies recruited individuals with FAIS from clinicians or hospital records, suggesting they
were at a more advanced symptomatic stage than participants in the present study, which could help explain the divergent findings. Additionally, in previous studies, physical activity levels were often higher in control compared to FAIS groups.\textsuperscript{23,39} Our findings suggest individuals with FAIS experience similar levels of fatigue compared to those with asymptomatic cam morphology. Future studies should aim to confirm these findings in individuals with FAIS who report higher levels of pain and lower levels of physical activity.

**Effect of repeated sprint exercise on pain in FAIS**

Despite observed reductions in maximal running speed and hip strength following repeated sprint exercise in all three groups, we found no significant changes in pain (NRS scale) during running in the FAIS group. Within the FAIS group, only 4 of 15 (27\%) participants demonstrated increased pain (NRS scale) after repeated sprint exercise despite 85\% of these participants having reported difficulty sprinting in the week prior testing (HAGOS subscale). The low levels of pain observed in our study are consistent with other reports during walking, bodyweight squatting, and cross-body lunging,\textsuperscript{9,19} and suggest repeated sprinting alone is not a cause for acute pain in most individuals with FAIS. However, we acknowledge that running in this study did not induce sufficient hip flexion to cause hip impingement\textsuperscript{3} and the short duration of the exercise bout (<15 minutes) may also have contributed to low levels of hip pain reported. Thus, our findings suggest repeated sprinting may not alter running patterns sufficiently to trigger acute symptoms in individuals with FAIS. Future studies should aim to investigate longer duration submaximal running or more provocative tasks such as pivoting, kicking, or twisting.

**Relationships between pain in the previous week and hip biomechanics during running and isometric hip strength**

We observed no significant relationships between hip pain reported during sporting activities in the week prior testing (HAGOS subscale) and changes in hip moments during running or
hip strength following the repeated spring exercise. Interestingly, participants who reported increased pain scores (NRS scale) following repeated sprint exercise also reported more severe symptoms in the week prior testing (HAGOS subscale) and exhibited larger reductions in hip abduction moments during running compared to baseline. Although our sample size does not allow sufficient statistical power to perform a subgroup analysis within the FAIS group, we observed heterogeneous pain responses (NRS scale) following repeated sprint exercise in participants with FAIS, which suggests the presence of subgroups should be further explored to understand the origin of symptoms in individuals with FAIS.

Strengths and limitations

This is the first study to investigate hip biomechanics during maximal effort running in individuals with FAIS. We included a sport-specific repeated sprint protocol, a comparison group with asymptomatic cam morphology only (no pincer morphology), and participant groups matched for physical activity levels. By assessing hip strength before and after a bout of repeated sprint exercise, we were able to verify the occurrence and extent of fatigue in each group. The main limitation was our small sample size that did not allow for a subgroup analysis of participants within the FAIS group based on pain responses to repeated sprints. Second, different proportions of male/female participants within groups may explain the absence of between-group differences. However, further inspection of data separated by sex (Supplementary Figures 5-7) suggests between-group differences in sex distribution had limited effect on reported hip biomechanics data, and a minimal effect on strength measures. Nevertheless, future cross-sectional studies should aim to match groups by sex. Third, 60° alpha angle threshold has recently been proposed as a cut-off for cam morphology. At the time of participant recruitment, a threshold was yet to be established, and thus we followed the commonly used cut-off of 55°. Fourth, we did not screen participants for other hip pathologies such as presence of cartilage or labral damage, which may have influenced our results.
Thus, future studies should screen participants for intra-articular damage, in addition to FAIS. Last, although included participants were recreationally active, their sporting background was heterogeneous, and results may differ if sport-specific populations are compared.

**Conclusion**

The association between frequent participation in high impact activities and development of cam morphology is well established in the literature,\[^{25,33}\] however the link between cam morphology and hip symptoms is less clear.\[^{19,25}\] We observed no differences in running speed, hip flexion angles, hip flexion and extension moments, and hip strength in all muscle groups between participants with FAIS and asymptomatic participants, with or without cam morphology, before or after a bout of repeated sprint exercise. We did not find any association between HAGOS scores and changes in hip biomechanics during running following repeated sprint exercise. Our results suggest a short bout of repeated sprint running (<15 minutes) does not elicit fatigue-related changes in running biomechanics in FAIS beyond what occurs in those without symptoms. Longer duration activities or activities requiring greater hip flexion combined with adduction and/or internal rotation may better provoke pathology-related changes in running biomechanics in those with FAIS.
### Tables

**Table 1.** Overview of maximal isometric strength testing set-up.

<table>
<thead>
<tr>
<th>Hip muscle action</th>
<th>Test position</th>
<th>Hip angle (°)</th>
<th>Knee angle (°)</th>
<th>Attachment position</th>
<th>Lever arm origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension</td>
<td>Standing</td>
<td>0F, 0ABD</td>
<td>0</td>
<td>Femoral condyle</td>
<td>Greater trochanter</td>
</tr>
<tr>
<td>Flexion (F)</td>
<td>Supine</td>
<td>45F, 0ABD</td>
<td>90</td>
<td>Femoral condyle</td>
<td>Greater trochanter</td>
</tr>
<tr>
<td>Abduction (ABD)</td>
<td>Supine</td>
<td>0F, 15ABD</td>
<td>0</td>
<td>Lateral malleolus</td>
<td>Greater trochanter</td>
</tr>
<tr>
<td>Adduction</td>
<td>Supine</td>
<td>0F, 15ABD</td>
<td>0</td>
<td>Lateral malleolus</td>
<td>Greater trochanter</td>
</tr>
<tr>
<td>External rotation</td>
<td>Sitting</td>
<td>90F, 0ABD</td>
<td>90</td>
<td>Lateral malleolus</td>
<td>Patella</td>
</tr>
<tr>
<td>Internal rotation</td>
<td>Sitting</td>
<td>90F, 0ABD</td>
<td>90</td>
<td>Lateral malleolus</td>
<td>Patella</td>
</tr>
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Table 2. Participant descriptive parameters for individuals with femoroacetabular impingement syndrome (FAIS), asymptomatic cam morphology (CAM), and healthy controls (Control).

<table>
<thead>
<tr>
<th></th>
<th>FAIS (n=15)</th>
<th>CAM (n=16)</th>
<th>Control (n=18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (female/male)</td>
<td>3 / 11</td>
<td>1 / 15</td>
<td>9 / 9</td>
</tr>
<tr>
<td>Age (years)</td>
<td>30.6 (5.2)*#</td>
<td>26.1(4.2)</td>
<td>25.2 (5.8)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>80.1 (13.2)</td>
<td>76.9 (9.9)</td>
<td>71.2 (10.9)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.7 (7.6)</td>
<td>179.8 (7.2)</td>
<td>173.6 (8.2)</td>
</tr>
<tr>
<td>BMI (kg.m⁻²)</td>
<td>25.5 (2.8)</td>
<td>23.7 (2.0)</td>
<td>23.5 (2.8)</td>
</tr>
<tr>
<td>Exercise (min.wk⁻¹)</td>
<td>415 (231)</td>
<td>368 (204)</td>
<td>433 (176)</td>
</tr>
<tr>
<td>Alpha angle (°)</td>
<td>64.6 (7.9)*</td>
<td>66.7 (6.8)*</td>
<td>45.9 (5.6)</td>
</tr>
<tr>
<td>Lateral centre edge angle (°)</td>
<td>20.0 (5.6)</td>
<td>20.9 (5.9)</td>
<td>21.4 (4.7)</td>
</tr>
<tr>
<td>Modified Tegner Scalea</td>
<td>6.4 (1.1)</td>
<td>6.5 (1.0)</td>
<td>6.8 (0.9)</td>
</tr>
<tr>
<td>FABER (n (%), positive)</td>
<td>10 (67)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FADIR (n (%), positive)</td>
<td>13 (87)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>iHOT-33b</td>
<td>56 (23-91)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAGOSb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symptoms</td>
<td>50 (29-93)</td>
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<tr>
<td>Pain</td>
<td>73 (40-85)</td>
<td></td>
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</tr>
<tr>
<td>Activities of daily living</td>
<td>80 (45-100)</td>
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<tr>
<td>Sports and recreational activities</td>
<td>61 (25-88)</td>
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<tr>
<td>Participation in physical activities</td>
<td>50 (0-100)</td>
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<tr>
<td>Quality of life</td>
<td>45 (20-85)</td>
<td></td>
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</tr>
</tbody>
</table>

Data are mean (one standard deviation) or median (range). FABER = flexion, abduction, external rotation test. FADIR = flexion, adduction, internal rotation test.

*a0 = disability, 10 = competitive sport at the professional level.
*b0 = extreme hip and/or groin problems, 100 = no hip and/or groin problems.
*indicates significant difference compared to Control (P<0.05).
#indicates significant difference compared to CAM (P<0.05).
Table 3. Spatiotemporal parameters during a 10-m maximal running trial before (Pre) and after (Post) repeated sprint exercise by group.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FAIS (n=15)</th>
<th>CAM (n=16)</th>
<th>Control (n=18)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximal speed (m.s⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>6.47 (0.52)</td>
<td>6.51 (0.45)</td>
<td>6.40 (0.46)</td>
</tr>
<tr>
<td>Post</td>
<td>5.54 (0.63) *</td>
<td>5.10 (0.66) *</td>
<td>5.13 (0.75) *</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>-14 (7)</td>
<td>-22 (8)</td>
<td>-20 (9)</td>
</tr>
<tr>
<td><strong>Maximal acceleration (m.s⁻²)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>2.32 (0.19)</td>
<td>2.29 (0.18)</td>
<td>2.27 (0.16)</td>
</tr>
<tr>
<td>Post</td>
<td>2.02 (0.22) *</td>
<td>1.89 (0.26) *</td>
<td>1.89 (0.23) *</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>-13 (7)</td>
<td>-18 (9)</td>
<td>-17 (9)</td>
</tr>
<tr>
<td><strong>Step time (s)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>0.49 (0.08)</td>
<td>0.49 (0.03)</td>
<td>0.50 (0.04)</td>
</tr>
<tr>
<td>Post</td>
<td>0.55 (0.08) *</td>
<td>0.61 (0.06) *</td>
<td>0.60 (0.07) *</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>12 (8)</td>
<td>25 (14)</td>
<td>20 (11)</td>
</tr>
<tr>
<td><strong>Contact time (s)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>0.17 (0.02)</td>
<td>0.16 (0.02)</td>
<td>0.17 (0.01)</td>
</tr>
<tr>
<td>Post</td>
<td>0.20 (0.02) *</td>
<td>0.20 (0.02) *</td>
<td>0.20 (0.03) *</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>19 (14)</td>
<td>28 (17)</td>
<td>22 (14)</td>
</tr>
<tr>
<td><strong>Step length (m)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>2.82 (0.60)</td>
<td>2.85 (0.29)</td>
<td>2.89 (0.24)</td>
</tr>
<tr>
<td>Post</td>
<td>2.74 (0.58)</td>
<td>2.90 (0.30)</td>
<td>2.82 (0.27)</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>-2 (8)</td>
<td>2 (10)</td>
<td>-2 (9)</td>
</tr>
<tr>
<td><strong>Step frequency (Hz)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>2.12 (0.52)</td>
<td>2.07 (0.14)</td>
<td>2.01 (0.19)</td>
</tr>
<tr>
<td>Post</td>
<td>1.89 (0.43) *</td>
<td>1.66 (0.15) *</td>
<td>1.68 (0.20) *</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>-10 (7)</td>
<td>-19 (9)</td>
<td>-16 (8)</td>
</tr>
</tbody>
</table>

Data are mean (one standard deviation). Differences calculated as \( \frac{Post - Pre}{Pre} \times 100 \).

*indicates significant difference between Pre and Post (P<0.05).

FAIS = femoroacetabular impingement syndrome; CAM = cam morphology.
Figures

Figure 1. Ensemble averages (±1 standard deviation, shaded) for hip angles before (Pre) and after (Post) repeated sprint exercise in the sagittal (top), frontal (middle), and transverse (bottom) planes across a running stride cycle in individuals with femoroacetabular impingement syndrome (FAIS, n=15), asymptomatic cam morphology (CAM, n=16), and in healthy controls (Control, n=18). Mean differences shown as post-pre (right). Dashed vertical lines indicate foot contact. No significant group-time interactions were observed as a result of a two-way repeated measures ANOVA using statistical parametric mapping. abd = abduction; add = adduction; ext = extension; ext rot = external rotation; flex = flexion; int rot = internal rotation.
Figure 2. Ensemble averages (±1 standard deviation, shaded) for hip internal moments before (Pre) and after (Post) repeated sprint exercise in the sagittal (top), frontal (middle), and transverse (bottom) planes across a running stride cycle in individuals with femoroacetabular impingement syndrome (FAIS, n=15), asymptomatic cam morphology (CAM, n=16), and in healthy controls (Control, n=18). Mean differences shown as post-pre (right). Dashed vertical lines indicate foot contact. No significant group-time interactions were observed as a result of a two-way repeated measures ANOVA using statistical parametric mapping. abd = abduction; add = adduction; ext = extension; ext rot = external rotation; flex = flexion; int rot = internal rotation.
Figure 3. Maximal isometric hip strength before and after repeated sprint exercise compared between individuals with femoroacetabular impingement syndrome (FAIS), asymptomatic cam morphology (CAM), and healthy controls (Control). Data are mean (bars), 95% confidence intervals (error bars). Participants in the FAIS group shown with (red dots) and without (grey dots) hip pain (≥1/10 on numerical rating scale) following repeated sprint exercise. *Significant effect of time as a result of a two-way analysis of variance. No between-group differences were observed.
**Supplementary figures**

Supplementary Figure 1. Schematic representation of the repeated sprint exercise (12 x 30-metre maximal sprints). *Participants were asked to complete twelve 30-metre sprints. Some participants could not complete the full protocol, while others required more trials to achieve a minimum of 8% reduction in maximal speed.
Supplementary Figure 2. Ensemble average (±1 standard deviation) hip angles in the sagittal (left), frontal (centre), and transverse (right) planes across a running stride cycle (displayed as toe-off to toe-off, foot contact represented with a vertical dashed line) before (pre, first row) after (post, second row) repeated sprint exercise in individuals with femoroacetabular impingement syndrome (FAIS, solid purple, n=15), asymptomatic cam morphology (CAM, dashed blue, n=16), and healthy controls (Control, dotted green, n=18). Results of a two-way repeated measures ANOVA using statistical parametric mapping are shown for the main effect of group (third row), main effect of time (fourth row), and interaction between group and time (fifth row).
**Supplementary Figure 3.** Ensemble average (±1 standard deviation) hip moments in the sagittal (left), frontal (centre), and transverse (right) planes across a running stride cycle (displayed as toe-off to toe-off, foot contact represented with a vertical dashed line) before (pre, first row) after (post, second row) repeated sprint exercise in individuals with femoroacetabular impingement syndrome (FAIS, solid purple, n=15), asymptomatic cam morphology (CAM, dashed blue, n=16), and healthy controls (Control, dotted green, n=18). Results of a two-way repeated measures ANOVA using statistical parametric mapping are shown for the main effect of group (third row), main effect of time (fourth row), and interaction between group and time (fifth row).
Supplementary Figure 4. Scatterplot for relationship between individual scores on the “Function, sports and recreational activities” subscale of the Copenhagen Hip and Groin Outcome Score (HAGOS) and changes (Δ) in peak hip moments during running (top) or isometric hip strength (bottom) following repeated sprint exercise in participants with femoroacetabular impingement syndrome. Participants who reported hip pain (≥1/10 on numerical rating scale) following repeated sprint exercise are shown in red.
Supplementary Figure 5. Individual hip angles over time comparing male (grey) and female (red) participants in the sagittal (top), frontal (middle), and transverse (bottom) planes across a running stride cycle in individuals with femoroacetabular impingement syndrome (FAIS, n=15), asymptomatic cam morphology (CAM, n=16), and in healthy controls (Control, n=18). abd = abduction; add = adduction; ext = extension; ext rot = external rotation; flex = flexion; int rot = internal rotation.
Supplementary Figure 6. Individual hip moments over time comparing male (grey) and female (red) participants in the sagittal (top), frontal (middle), and transverse (bottom) planes across a running stride cycle in individuals with femoroacetabular impingement syndrome (FAIS, n=15), asymptomatic cam morphology (CAM, n=16), and in healthy controls (Control, n=18). abd = abduction; add = adduction; ext = extension; ext rot = external rotation; flex = flexion; int rot = internal rotation.
Supplementary Figure 7. Maximal isometric hip strength before and after repeated sprint exercise compared between individuals with femoroacetabular impingement syndrome (FAIS), asymptomatic cam morphology (CAM), and healthy controls (Control). Data are mean (bars), 95% confidence intervals (error bars). Male (red dots) and female (grey dots) participants are shown.
**Supplementary Methods**

**Magnetic resonance imaging**

Three-dimensional, T2 weighted axial sequences were acquired with a 3T MRI unit (Ingenia, Phillips Medical System, Amsterdam, Netherlands) from the top of the iliac crest to mid-thigh (resolution = 0.57 mm x 0.57 mm x 1 mm). Participants were positioned supine with both hips in 0° of adduction and internal/external rotation. Using Horos Version 2.0 (Nimble & co, Annapolis, USA, horosproject.org), alpha angle was measured in 4 oblique planes spanning the anterior superior region of the femoral head-neck junction, around the longitudinal axis of the femoral neck at 0° (superior), 30° (anterosuperior), 60° (anterosuperior), and 90°(anterior) (i.e. 12, 1, 2, and 3 o’clock positions). For every image plane, an ideal circle was manually fitted to the femoral head and the angle between the line connecting the longitudinal axis of femoral neck to the center of the circle and the line connecting the center of the circle to the first instance where the femoral head extended beyond the margin of the circle was calculated as the alpha angle. Lateral center edge angle was measured in the coronal plane to determine the degree of acetabular coverage and presence of pincer morphology (i.e.>39°). Lateral center edge angle was defined as the angle between a line from the center of the femoral head parallel to the longitudinal axis of the body and a line from the center of the femoral head to the most lateral aspect of the acetabular the sourcil edge. Maximum alpha angle and lateral center edge angle for each participant were used for group classification and statistical analysis. The same investigator (EM) performed all measurements. Intra-observer reliability was assessed using Intraclass correlation coefficients (ICC) and standard error of measurement (SEM) with 95% confidence intervals (CI) of alpha angle and lateral center edge angle measurements performed on separate days in 19 random participants. Both alpha angle (ICC [95%CI] = 0.89 [0.83 to 0.93], SEM = 3.8° [3.3° to 4.5°]) and lateral center edge angle (ICC = 0.87 [0.78 to 0.93], SEM
measurements showed good-to-excellent levels of intra-observer reliability.3

Data processing

All data were recorded using Vicon Nexus 2.7.1 software (Vicon, Oxford Metrics Group, UK) at 2000 Hz (GRF and isometric force data) or 200 Hz (marker coordinates). Isometric force data were low-pass filtered using a 2nd order, dual-pass, zero-lag Butterworth filter with a nominal cut-off frequency of 6 Hz using custom scripts in MATLAB R2018b (MathWorks, MASS, USA). Maximum force values were calculated as the maximum 100 ms moving average. Maximum force value per task, per participant, per time point were used for subsequent analysis. Force data were converted to torque (N·m) by multiplying the maximum force (N) by the lever arm (m) (Table 1). For each participant, pre to post torque percent differences were calculated as a mean difference (MD=(post-pre)/pre×100).

Marker trajectories were low-pass filtered using a 2nd order, dual-pass, zero-lag Butterworth filter with a nominal cut-off frequency of 10 Hz and GRF were unfiltered.4 For each participant, a generic full-body model5 with 37 degrees of freedom was linearly scaled to match individual anthropometry based on marker positions and regression-estimated joint centers.5 The scaled model was then used to determine hip sagittal, frontal, and transverse plane kinematics and internal moments using the inverse kinematics and inverse dynamics OpenSim tools,6 respectively. Joint moments were normalized to body mass (Nm·kg⁻¹). Gait events were visually inspected to identify foot-contact and toe-off events based on foot marker positions and vertical ground reaction forces. Stride cycles were manually cropped between consecutive ipsilateral toe-off events. Given laboratory restrictions, initial toe-off was defined based on visual inspection of marker position and velocities. Foot strike and second toe-off were defined as the first and last frame with vertical GRF above 10N respectively. Therefore, gait events...
included in the analyzed stride cycles included initial toe-off, foot-contact, and subsequent toe-off. Joint kinematics and moments were normalized to the duration of the stride cycle (%). Maximal running speed (m·s\(^{-1}\)) and acceleration (m·s\(^{-2}\)) were determined across the stride cycle as the first and second derivative of the pelvis horizontal position with time. Stride length (m) and stride time (s) were calculated as the antero-posterior displacement of the marker placed on top of the first metatarsal and time between two consecutive ipsilateral toe-offs, respectively. Stride frequency (Hz) was calculated as the inverse of stride time (s). Contact time (s) was calculated as time between foot-contact and toe-off.

**Statistical analysis**

Demographics, spatiotemporal parameters, and torque data were inspected for normality using the Shapiro-Wilk test. With the exception of baseline step frequency and step time for the control group, all spatiotemporal and strength parameters showed no deviations from normality. We used a two-way repeated measures analysis of variance (ANOVA) to analyze the interactions and main effects of group (FAIS, CAM, Control) and/or time (pre, post) on each spatiotemporal and strength measures. When a significant interaction or main effect was observed, post-hoc comparisons between groups were made using either independent sample t-tests or Mann-Whitney U-tests and post-hoc pairwise comparisons between time points were made using either paired sample t-tests or Wilcoxon Sign tests. A Bonferroni correction was used for multiple comparisons to reduce the chance of Type-I error. Pain scores (NRS scale) were compared from pre to post in the FAIS group using a Wilcoxon Sign test. A two-way repeated measures ANOVA was performed to assess differences between groups and time points for hip angles and moments using statistical parametric mapping. Bonferroni post-hoc pairwise comparisons were performed if significant interactions between group and time were found. Spearman’s rank correlation coefficients (\(\rho\)) were used to evaluate the relationships...
between hip pain in the week prior testing (HAGOS subscale scores) and (i) changes in maximal running speed, (ii) changes in peak hip moments during running, and (iii) changes in isometric hip strength, in the FAIS group only. Relationships were only evaluated for hip flexion, extension, and abduction moments and corresponding muscle groups given these are meaningful for straight-line running. The relationship between variables was classified as small ($\rho=0.1$), medium ($\rho=0.3$), or large ($\rho=0.50$). Statistical analyses were performed using MATLAB R2018b and RStudio (version 1.2.5, Boston, US). Significance was accepted for $P<0.05$. 
References


