



## Full length article

# Modified gait patterns due to cam FAI syndrome remain unchanged after surgery

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## ABSTRACT

**Background:** In order to reduce the development of hip osteoarthritis related to cam-type femoroacetabular impingement syndrome (FAIS), corrective surgery has evolved to become a safe and effective treatment. Although corrective surgery produces high level of patient satisfaction, it is still unclear how it affects muscle and hip contact forces during level walking.

**Research question:** The purpose was to compare the muscle force contributions and hip contact forces in patients before and after surgical correction for cam FAIS with healthy control (CTRL) individuals during level walking.

**Methods:** Eleven male patients with symptomatic cam-type morphology, who underwent hip osteochondroplasty, had their level walking recorded pre- and at 2-year postoperatively. The patients were sex-, age-, BMI-matched to 11 CTRL individuals. Sagittal and frontal hip kinematics and kinetics were computed and, subsequently, muscle and hip contact forces were estimated using musculoskeletal modelling and static optimization.

**Results:** Patient-reported outcomes improved postoperatively. The pre- and postoperative FAIS walked slower and with shorter steps than the CTRL. Postoperative biceps femoris (CTRL:  $0.35 \pm 0.13$  N/BW; pre-op:  $0.28 \pm 0.11$  N/BW; post-op:  $0.20 \pm 0.07$  N/BW) and semimembranosus forces (CTRL:  $0.77 \pm 0.24$  N/BW; pre-op:  $0.66 \pm 0.24$  N/BW; post-op:  $0.41 \pm 0.14$  N/BW) were lower at ipsilateral foot-strike. Postoperative rectus femoris force (CTRL:  $1.73 \pm 0.35$  N/BW; pre-op:  $1.44 \pm 0.24$  N/BW; post-op:  $1.18 \pm 0.23$  N/BW) was lower than the other two groups, and the pre- and postoperative FAIS had lower iliopsoas (CTRL:  $1.17 \pm 0.18$  N/BW; pre-op:  $0.93 \pm 0.16$  N/BW; post-op:  $0.94 \pm 0.21$  N/BW) and psoas (CTRL:  $1.55 \pm 0.24$  N/BW; pre-op:  $1.14 \pm 0.38$  N/BW; post-op:  $1.10 \pm 0.46$  N/BW) muscle forces at contralateral foot-strike compared with the CTRL. Pre- and postoperative FAIS demonstrated lower peak hip contact loading resultant than the CTRL.

**Significance:** The altered gait parameters observed in the preoperative FAIS was not restored after surgery, and was still away from the CTRL. It is possible that the reduced dynamic muscle forces of the biceps femoris, semimembranosus and rectus femoris postoperatively were associated with the protected mechanism that involved the iliopsoas preoperatively. This is an indication that the gait adaptations affected by the FAIS do not restore to normal after surgical correction at the 2-years follow-up.

## 1. Introduction

Cam-type femoroacetabular impingement syndrome (FAIS) is caused by an aspherical femoral head that abuts against the acetabular rim during hip flexion. This can lead to chondral abrasion and labral detachment, causing pain in the groin and the development of early adult hip osteoarthritis [1,2]. Patients are initially treated through

conservative nonsurgical methods, but osteochondroplasty of the femoral head-neck junction is often required [3–5]. The surgery can be done through either open [6,7] or arthroscopic [8,9] approaches, with both producing high level of patient satisfaction [10–12].

Prior to surgery, symptomatic cam FAIS patients demonstrate altered biomechanics during gait [13–16], squatting [17–19], and stairs climbing [20,21], indicating reduced hip and pelvic range of motion

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(ROM), and hip flexion and external rotation moments compared to healthy controls (CTRL). Neuromuscular adaptations may influence biomechanical outcomes as patients with FAIS demonstrate weaker hip isometric muscle strength during flexion, extension, abduction, adduction, and external rotation movements [22–25]. These adaptations were demonstrated in a musculoskeletal modelling study that indicated reduced psoas major and iliacus muscle forces during gait in symptomatic patients compared with CTRL [26].

There is no clear consensus on the effect of surgery on biomechanical outcomes, which ranged from no improvements at all [27], improved sagittal and internal hip ROM [16,20], and even reduced hip ROM [28]. Patient-reported outcome measures have indicated that surgery alleviates pain and improves quality of life [10–12], but quantitative evidence to support these findings is still lacking. In other words, how FAIS correction surgery alters the muscle forces generated at the hip or how it affects hip contact loading is not well known. Therefore, the primary purpose of this study was to compare muscle force contributions and hip contact forces in patients before and after surgical correction for cam FAIS during level walking. The side comparison was to match them with CTRL data.

## 2. Methods

### 2.1. Participants

Eighteen male patients presented themselves to the senior orthopaedic surgeon's practice with persisting unilateral clinical signs of hip pain and positive impingement tests. They underwent pelvic and knee computed tomography (CT) scan (Acquilion, Toshiba Medical Systems Corporation, Otawara, Japan; or Discover CT750, GE Healthcare, Mississauga, ON, Canada), to confirm cam-type FAIS morphology, as defined by an axial (3:00) or radial (1:30) alpha angle larger than 50.5° and 60°, respectively [29,30]. Participants were excluded if they indicated any other hip morphology, a history of severe lower limb traumas or surgeries, or had a body mass index (BMI) greater than 30 kg/m<sup>2</sup>. All patients underwent corrective surgery by the same senior surgeon (e.g. osteochondroplasty and labral-chondral debridement). Twelve patients return to the laboratory for the postoperative biomechanical assessment, and the data of one of the returning patients was found corrupt afterwards. Therefore, 11 FAIS patients were included in this study, whose surgical approaches were either open dislocation (n = 4) or arthroscopic (n = 7). These were age-, BMI- and sex-matched to 11 CTRL individuals who were cam-free and have no history of hip pain. Motion analysis protocol and completion of the Hip Disability and Osteoarthritis Outcome Score (HOOS) questionnaire were performed preoperatively (up to two months before) and at 2-years postoperatively (24.2 ± 1.5 months). The study was approved by the hospital and institution research ethics boards, and all participants provided voluntary informed consent.

### 2.2. Motion analysis

To improve marker placement during motion analysis, radiopaque surface markers were placed on the participants before CT imaging. These markers were placed on the anterior superior iliac spines, posterior superior iliac spines, medial and lateral epicondyles. At the motion capture laboratory, the radiopaque markers were then replaced with retro-reflective markers and outfitted according to the University of Ottawa Motion Analysis Model (UOMAM) marker set [31]. Participants performed five barefoot level walking trials, at a self-selected pace, where marker trajectories were captured using a ten-infrared camera system sampled at 200 Hz (Vicon MX-13, VICON, Oxford, UK) and ground reaction forces were captured using two embedded force plates at 1000 Hz (FP4060-08, Bertec Corporation, Columbus, USA). The data were labelled and filtered (zero-lag, fourth order Butterworth filter, cut-off frequency = 6 Hz), walking speed and stride length were

calculated using motion analysis software (Nexus 2.6.1, VICON, Oxford, UK). The gait analyses were performed during the stance phase (i.e., ipsilateral foot-strike to foot-off) and all gait variables were time-normalized to its cycle.

### 2.3. Musculoskeletal modelling

A generic musculoskeletal model [32] consisting of 37 degrees of freedom, 80 lower-limb Hill-type muscle-tendon units, and 17 torque actuators driving the upper body was used in an open-source musculoskeletal simulation software (OpenSim™ 3.3, Stanford University, Stanford, USA) [33]. This model has shown qualitative agreement from experimental electromyography data for walking and running tasks [32].

The marker trajectories and ground reaction forces were imported [34], and the generic model was scaled for each participant based on their static pose, with the pelvis and knee markers having a ten-times higher weight as their location was previously verified in the CT imaging. Joint kinematics and net joint moment for each degree of freedom were computed using the inverse kinematics and inverse dynamics tools. The muscle forces were calculated while minimizing the sum of squared muscle activation using the static optimization tool. Hip contact forces were reported as three-dimensional vectors acting on the acetabulum and expressed in the pelvic coordinate system. Both hip contact and muscle forces were normalized by body weight.

### 2.4. Statistical analysis

Intrasubject pre- and postoperative differences for demographics and gait parameters were examined using paired samples *t*-tests. Intrasubject peak sagittal and frontal hip kinematics and kinetics were compared between conditions using a paired *t*-test, and hip contact and muscle forces were compared using either a paired samples *t*-test or a Wilcoxon signed-rank test for non-parametric distributions, given that some of the variables failed the Shapiro-Wilk normality test (CI = 95%). Comparisons between the FAIS groups with the CTRL group were done using one-way ANOVA, followed by post hoc comparisons using Bonferroni corrections, to avoid a type II error. Statistical analyses were performed using statistics software (SPSS Statistics v.23, IBM Corporation, Armonk, USA).

## 3. Results

### 3.1. Demographics and patient reported outcome measures

Postoperatively, patients did not differ in BMI from their preoperative values (Table 1) and showed improvements in all HOOS categories when assessed two years following the surgery (Table 2). Still, postoperative scores were significantly lower than the CTRL values in

**Table 1**

Patient demographics, and cam deformity measurement; reporting mean ± SD.

Parameter	CTRL	FAIS pre	FAIS post	
Participants (n)	11	11		
Age (years)	33.9 ± 7.0	34.1 ± 7.4	36.2 ± 7.2	
Height (cm)	174.8 ± 6.1	177.3 ± 6.2	178.1 ± 7.2	
BMI (kg/m <sup>2</sup> )	25.3 ± 2.9	25.4 ± 2.7	25.6 ± 3.6	
alpha-angle (deg)	3:00 clock-face position	42.9 ± 3.1	54.0 ± 7.2	45.6 ± 6.7
	1:30 clock-face position	52.9 ± 4.4	66.3 ± 5.4	52.5 ± 9.1

CTRL, control; FAIS, femoroacetabular impingement syndrome.

\* The FAIS pre-op group differed significantly from the CTRL and FAIS post-op groups (*P* < .05).

**Table 2**  
Summary of pain questionnaire, and walking speed, and stride length parameters, normalized by leg length (LL) of each patient condition; reporting mean ± SD.

Parameter	CTRL	FAIS pre	FAIS post	P value		
				pre vs. post	CTRL vs. pre	CTRL vs. post
HOOS						
Symptoms	99.1 ± 2.0	70.0 ± 10.7	81.4 ± 10.0	.04	.01	< .01
Pain	97.7 ± 5.1	70.0 ± 16.9	90.0 ± 8.3	< .01	< .01	.02
Activities of Daily Living	99.2 ± 1.8	81.7 ± 15.1	95.3 ± 6.6	< .01	< .01	.62
Sports and Recreational Activities	96.0 ± 7.5	56.8 ± 25.1	83.0 ± 13.7	< .01	< .01	.19
Quality of Life	94.3 ± 12.6	39.2 ± 21.8	65.9 ± 21.5	.01	< .01	< .01
Walking Speed (m/s/LL)	1.67 ± 0.15	1.44 ± 0.17	1.44 ± 0.09	.91	< .01	< .01
Stride Length (m/LL)	1.70 ± 0.12	1.55 ± 0.15	1.55 ± 0.08	.97	.02	.02

CTRL, control; FAIS, femoroacetabular impingement syndrome; HOOS, Hip disability and Osteoarthritis Outcome Score.

three categories: Symptoms, Sports and Recreational Activities, and Quality of Life. A detailed demographics table with each patient information is included in the Appendix.

3.2. Gait parameters

No differences in walking speed or stride length were observed between pre- and postoperative FAIS patients, however, both pre- and postoperative FAIS patients walked slower and with smaller step length in comparison with the CTRL individuals (Table 2). The preoperative FAIS patients demonstrated reduced hip abduction at ipsilateral foot-off (IFO) compared to the postoperative ( $P = .041$ ) and the CTRL ( $P = .018$ ). The postoperative demonstrated lower hip extension moment at ipsilateral foot-strike (IFS) compared to the preoperative ( $P = .007$ ) and the CTRL ( $P < .001$ ) and lower hip extension moment during contralateral foot-strike (CFS) compared to the preoperative ( $P = .004$ ) and the CTRL ( $P = .039$ ) – Fig. 1.

3.3. Muscle and hip contact forces

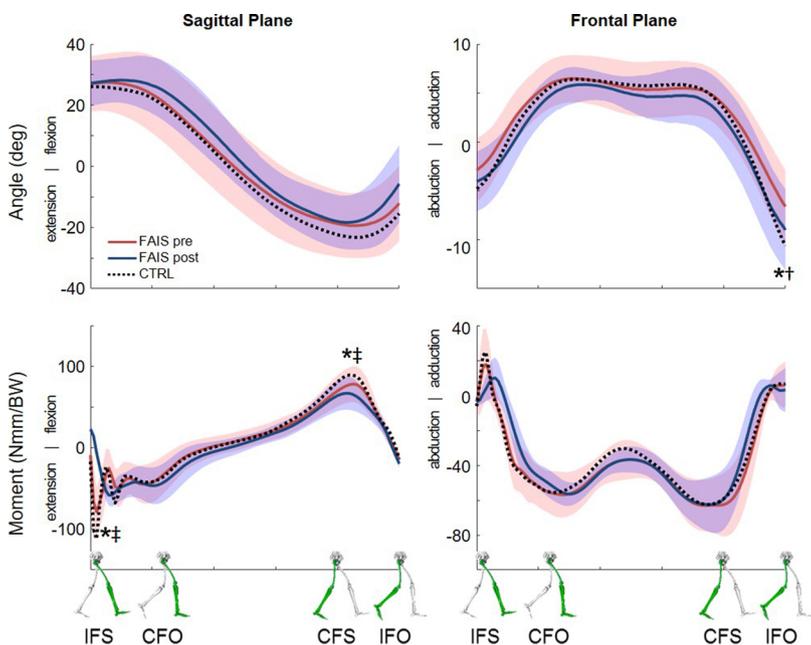
Postoperative FAIS demonstrated significantly reduced biceps femoris (long head) and semimembranosus forces during IFS when compared to the preoperative values ( $P = .019$ ,  $P = .008$ , respectively), and when compared with the CTRL group ( $P = .008$ ;  $P < .001$  respectively). Lower rectus femoris force was observed postoperatively at CFS compared with the preoperative ( $P = .039$ ) and the CTRL ( $P < .001$ ) groups. No significant differences in muscle forces between

FAIS conditions were detected for the gluteus maximus, iliacus or psoas muscles. However, pre- and postoperative FAIS showed differences when compared to the CTRL group for the iliacus ( $P = .011$ ,  $P = .015$ ) and psoas ( $P = .037$ ,  $P = .020$ ), respectively (Fig. 2).

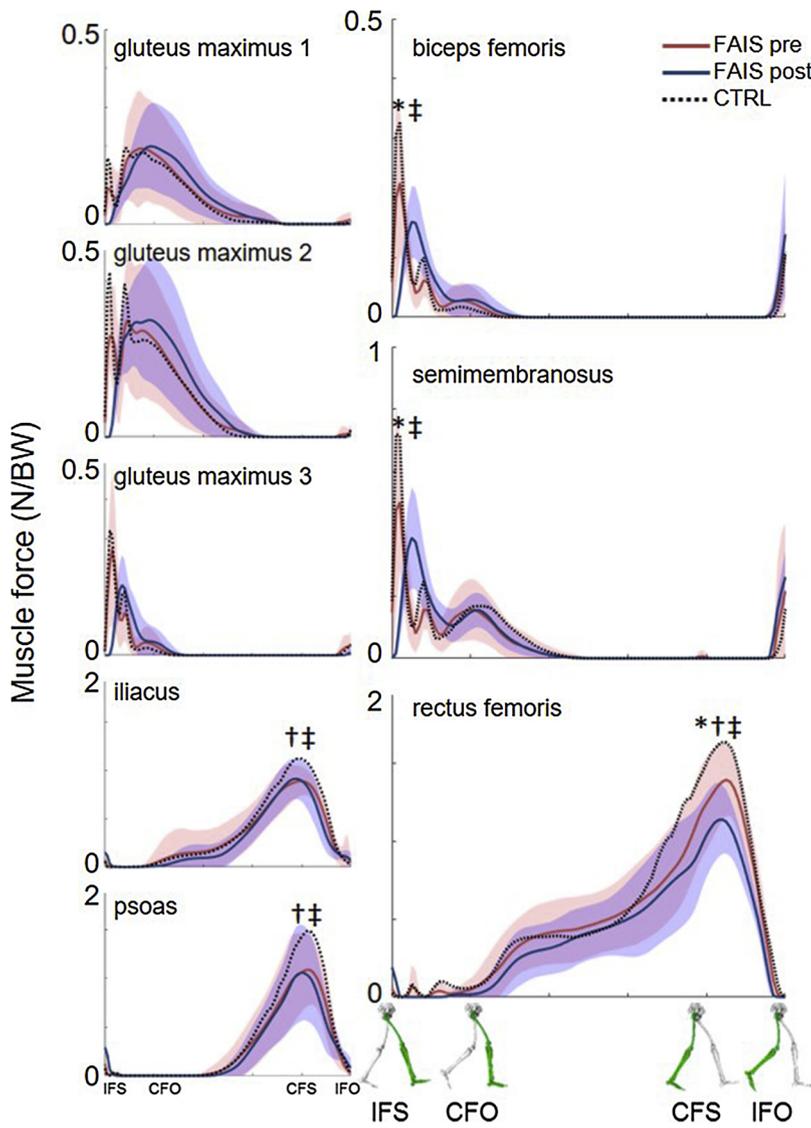
There were no differences between pre- and postoperative peak hip contact forces in the anterior ( $P = .43$ ), superior ( $P = .32$ ), or medial ( $P = .10$ ) directions. However, they both showed lower superior peak forces when compared with the CTRL group ( $P = .021$ ,  $P = .008$ , respectively). Also, the postoperative group showed lower anterior peak forces when compared with the CTRL group ( $P = .018$ ) (Fig. 3A). Resultant peak forces vectors, during CFS, were similar between preoperative ( $4.82 \pm 1.04$  N/BW) and postoperative ( $4.63 \pm 0.70$  N/BW;  $P = .20$ ), however pre- and postoperative FAIS were significantly lower than the CTRL ( $6.25 \pm 1.38$  N/BW; vs pre-op:  $P = .011$ ; vs post-op:  $P = .004$ ) (Fig. 3B).

4. Discussion

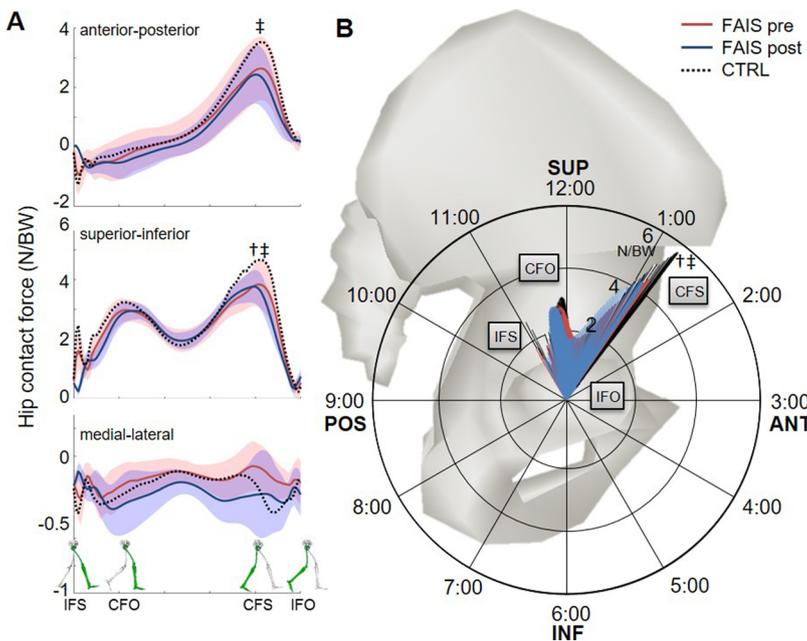
At the two-year follow-up, patients showed significant improvement scores in the patient-reported outcomes. They also showed reduced forces in the long head of the biceps femoris and semimembranosus at IFS, and in the rectus femoris at CFS. Muscle forces of the iliacus and psoas major of pre- and postoperative FAIS were lower when compared to the CTRL group. While there were no differences in hip contact force magnitudes before and after surgical correction, the FAIS patients demonstrated lower peak hip contact forces in the anterior (post-op) and superior directions (pre- and post-op) when compared with the CTRL,



**Fig. 1.** Hip joint angles (top row) and moments (bottom row) in the sagittal (left), frontal (right) planes, during the gait cycle, for the FAIS preoperative (red), postoperative (blue) and CTRL (black) conditions. Hip joint moments were normalized by body-weight (BW) and the full stance phase was represented at ipsilateral foot-strike (IFS), contralateral foot-off (CFO), contralateral foot-strike (CFS), ipsilateral foot-off (IFO). The asterisk (\*) denotes the statistical difference between the FAIS groups ( $P < .05$ ) in hip adduction angle, and hip flexion and extension moments. The CTRL demonstrated significantly higher hip adduction angle than the FAIS pre (†), and greater hip flexion and extension moments than the FAIS post (‡).



**Fig. 2.** Muscle forces during the gait cycle, for the FAIS pre-operative (red), postoperative (blue) and CTRL (black) conditions. Muscle forces were normalized by body weight (BW) and determined from static optimization. The full stance phase was represented at ipsilateral foot-strike (IFS), contralateral foot-off (CFO), contralateral foot-strike (CFS), ipsilateral foot-off (IFO). The FAIS post demonstrated significantly lower muscle forces than the preoperative group (\*) for the biceps femoris (long head – top right), semimembranosus (middle right) and rectus femoris (bottom right). The CTRL demonstrated significantly higher muscle forces than the FAIS pre (†) for the iliacus, psoas (bottom left) and rectus femoris; and higher muscle forces than the FAIS post (‡) for the iliacus, psoas, biceps femoris, semimembranosus and rectus femoris.



**Fig. 3. A.** Hip contact forces during the gait cycle, for the FAIS preoperative (red), postoperative (blue) and CTRL (black) conditions, in all three planes. The full stance phase was represented at ipsilateral foot-strike (IFS), contralateral foot-off (CFO), contralateral foot-strike (CFS), ipsilateral foot-off (IFO). The CTRL demonstrated significantly higher forces in the superior direction than the FAIS pre (†), and in the anterior and superior directions than the FAIS post (‡). **B.** The resultant average hip contact forces during the gait cycle (right), depicted in the sagittal plane of a right hip. Hip contact forces were normalized by bodyweight (BW) and reported with a ‘butterfly’ graph, showing magnitude (radar graph) and direction (acetabular orientation) in respect to the pelvic coordinate system. Ant, anterior; Inf, inferior; Pos, posterior; Sup, superior.

causing a reduced peak force magnitude during CFS. At the two-year follow-up, the postoperative walking speed or stride length remained comparable to the preoperative conditions. Our findings corroborate with a previous study that showed that FAIS patients naturally walk slower and with shorter steps, compared to CTRL individuals [26]. This perhaps evidenced some persistent adaptive mechanisms after years of dealing with pain or awaiting surgery. Brisson and associates (2013) [28] analyzed level walking in 10 postoperative FAIS patients with a mixed gender group (7 men) and with unfixed follow-up (range 10–32 months) and did not find any significant change in hip and pelvic kinematics, or joint torques. The controlled sex inclusion and consistent follow-up time in our current study demonstrated that patients reduced hip adduction during IFO and hip extension moment during CFS. The inconsistency among previous studies that compared pre- and postoperative FAIS [16,20,27,28,35] suggest that underlying symptoms can be associated with soft tissue impairment or iatrogenic instability (i.e., suboptimal muscle strengthening and capsular instability), rather than the surgical osteochondroplasty [16,36].

The cam morphology is unlikely to impinge during a low amplitude motion [37], such as level walking; however, musculoskeletal modelling outputs (i.e. muscle and hip contact forces) can be very beneficial to highlight postoperative alterations observed in kinematics and kinetics. Moreover, the understanding of muscle contributions towards joint loading may provide benefits to design a better strategy for surgical intervention and rehabilitation [38,39]. Although several studies reported postoperative joint kinematics and kinetics associated with cam FAIS [16,20,27,28,35], none of them determined muscle or hip contact forces from musculoskeletal modelling. Ng and associates (2018) [26] reported musculoskeletal modelling outputs only in preoperative FAIS population during gait. This study showed that the limited hip mobility was associated with the reduced muscle force pattern of the iliopsoas muscle complex, which caused a reduction of the anterior, superior, and medial hip contact forces in FAIS patients [26].

The present study reported the forces of the major hip flexors and extensors to assess muscular post-surgical effects during level walking. However, as gait parameters (i.e., walking speed, stride length), joint kinematics (i.e., hip extension, hip and pelvic range of motion), and spinopelvic anatomy (i.e., pelvic tilt and incidence) did not change after surgery [39], there were marginal differences towards the simulated muscle force contributions of the primary hip flexors. For the muscles responsible for the hip extension, both the biceps femoris and the semimembranosus generate an extension moment during IFS. The reduced peak hip extension moment observed in the postoperative patients (Fig. 1) can be considered as the main reason for the optimization calculations to show a reduced force in the biceps femoris and the semimembranosus at this phase of the gait. It has been speculated that the decreased muscle forces on the hamstrings (biceps femoris and semimembranosus) and the rectus femoris, during IFS and CFS respectively, could be associated with the protected mechanism involving the iliopsoas preoperatively [23], suggesting that the preoperative gait adaptations remain unchanged postoperatively. This preventive pain mechanism may have generated neuromuscular adaptations in the long-term that affected muscle contraction strategies even at 2-year after surgery when pain no longer plays a role in the motion (Table 2). The decreased hip flexion moment at the contralateral foot strike can be directly associated with the also decreased muscle activation of the hip flexors. Once the dynamic force of the iliopsoas complex was already lower preoperatively, the co-contraction of the hip flexors during this flexion moment can justify, the force reduction of the rectus femoris. Likewise, a recent study has reported that patients with unilateral FAIS have a decreased rectus femoris cross-sectional area in the symptomatic hip compared with its asymptomatic counterpart [40]. And considering that multiple studies have previously reported decreased isometric hip flexor strength in FAIS patients [22–25], it could be argued that reduced cross-sectional area of the rectus femoris could have also

contributed to its force reduction generated dynamically. Yet, one may presume that the reduced forces indicate a more effective gait pattern, as they did not affect the kinematics, however, some caution must be kept regarding the interpretation of this lower muscle force, mainly because hip flexor strength [22,24] does not improve after surgery [41], and the gait kinematics were similar to the preoperative data.

These indications provide insights to clinicians and physiotherapists that rehabilitation sections focusing on hip and pelvis mobility increasing and hip muscle strengthening should not be overlooked. As higher joint ROM and stronger muscles are necessary to the increase walking speed and stride length to CTRL levels.

The small changes in hip contact forces during level walking merit the need of studies focusing the pre-post assessment during a motion involving a higher range of motion (e.g., deep squat) or with a higher hip stabilization request (e.g., step down). These type of tasks may provide a better understanding of muscle forces in a more demanding motion and its implications on the hip contact loading. Therefore, to perform these simulations, a model optimized to keep realistic muscle-tendon moment arms during large hip and knee flexions must be used; which can be controlled by using customized wrapping surfaces [42].

Some limitations affected this study. First, the sample size was underpowered, even though it is expected that this sort of study would presumably have a small cohort of patients. As our patients were all male and had cam-only FAIS morphology (no pincer or mixed), the inference from our findings is limited for only this population. Second, our cohort consisted of patients that underwent either a surgical dislocation or arthroscopy approach, although an independent comparison did not point to any statistical differences between these two postoperative management. Third, the muscle forces were calculated using a static optimization approach that may not perfectly express co-contraction mechanisms altered by a joint pathology; however, this method has the advantage of not requiring invasive access of deep muscles to perform EMG-driven simulations, and it also provides comparable muscle activations during various walking speeds [43]. Fourth, we modelled a specific hip pathology onto an idealized musculoskeletal model. Since the subject-specific hip bony morphology could not be directly assessed or parameterized in the model, which might have greatly influenced hip contact forces outputs. Fifth, although all patients were instructed to undergo an eight-week postsurgical rehabilitation program, the aftercare rehabilitation program was not controlled, which may have affected the benefit of this procedure for the patients the same way. Sixth, with ongoing strengthening and training, the postoperative patients may further adapt their walking mechanics. It would be feasible as a longitudinal study to conduct another follow-up in efforts to examine if there will be further improvements to gait mechanics or characteristics to healthy CTRL groups.

## 5. Conclusion

To our knowledge, this is the first study to evaluate muscle and hip contact forces, to compare preoperative and postoperative FAIS patients. The gait adaptations affected by the FAIS syndrome remain unchanged after 2-years post-surgery, not returning to normal standards. It is possible that the reduced dynamic muscle forces of the biceps femoris, semimembranosus and rectus femoris postoperatively were associated with a protected mechanism that involved the iliopsoas preoperatively, resulting in lower hip contact forces in FAIS patients.

## Author contributions

All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted.

## Conflicts of interest

The authors declare no conflicts of interest specifically with this study.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.gaitpost.2019.06.003>.

## References

- R. Ganz, J. Parvizi, M. Beck, M. Leunig, H. Nötzli, K.A. Siebenrock, Femoroacetabular impingement: a cause for osteoarthritis of the hip, *Clin. Orthop. Relat. Res.* (2003) 112–120, <https://doi.org/10.1097/01.blo.0000096804.78689.c2>.
- R. Ganz, M. Leunig, K. Leunig-Ganz, W.H. Harris, The etiology of osteoarthritis of the hip: an integrated mechanical concept, *Clin. Orthop. Relat. Res.* 466 (2008) 264–272, <https://doi.org/10.1007/s11999-007-0060-z>.
- D. Hunt, H. Prather, M.H. Hayes, J.C. Clohisey, Clinical outcomes analysis of conservative and surgical treatment of patients with clinical indications of prearthritic, intra-articular hip disorders, *PmR* 4 (2012) 479–487, <https://doi.org/10.1016/j.pmrj.2012.03.012>.
- J.K. Loudon, M.P. Reiman, Conservative management of femoroacetabular impingement (FAI) in the long distance runner, *Phys. Ther. Sport* 15 (2014) 82–90, <https://doi.org/10.1016/j.ptspt.2014.02.004>.
- P.E. Beaulé, J.C. Clohisey, P. Schoenecker, Y.-J. Kim, M. Millis, R.T. Trousdale, Hip arthroscopy: an emerging gold standard, *Arthroscopy* 23 (2007) 682, <https://doi.org/10.1016/j.arthro.2007.03.007>.
- M. Lincoln, K. Johnston, M. Muldoon, R. Santore, Combined arthroscopic and modified open approach for cam femoroacetabular impingement: a preliminary experience, *Arthroscopy* 25 (2009) 392–399, <https://doi.org/10.1016/j.arthro.2008.12.002>.
- F. Laude, E. Sariali, A. Nogier, Femoroacetabular impingement treatment using Arthroscopy and Anterior approach, *Clin. Orthop. Relat. Res.* 467 (2009) 747–752, <https://doi.org/10.1007/s11999-008-0656-y>.
- M.J. Philippon, A.J. Stubbs, M.L. Schenker, R.B. Maxwell, R. Ganz, M. Leunig, Arthroscopic management of femoroacetabular impingement: osteoplasty technique and literature review, *Am. J. Sports Med.* 35 (2007) 1571–1580, <https://doi.org/10.1177/0363546507300258>.
- M. Horisberger, A. Brunner, R.F. Herzog, Arthroscopic treatment of femoroacetabular impingement of the hip: a new technique to access the joint, *Clin. Orthop. Relat. Res.* 468 (2010) 182–190, <https://doi.org/10.1007/s11999-009-1005-5>.
- I.B. Botser, T.W. Smith, R. Nasser, B.G. Domb, Open surgical dislocation versus arthroscopy for femoroacetabular impingement: a comparison of clinical outcomes, *Arthroscopy* 27 (2011) 270–278, <https://doi.org/10.1016/j.arthro.2010.11.008>.
- B.G. Domb, C.E. Stake, I.B. Botser, T.J. Jackson, Surgical dislocation of the hip versus arthroscopic treatment of femoroacetabular impingement: a prospective matched-pair study with average 2-year follow-up, *Arthroscopy* (2013), <https://doi.org/10.1016/j.arthro.2013.06.010>.
- M.J. Philippon, Y.M. Yen, K.K. Briggs, D.A. Kuppersmith, R.B. Maxwell, Early outcomes after hip arthroscopy for femoroacetabular impingement in the athletic adolescent patient: a preliminary report, *J. Pediatr. Orthop.* (2008), <https://doi.org/10.1097/BPO.0b013e318186eb2e>.
- M.A. Hunt, J.R. Gunther, M.K. Gilbert, Kinematic and kinetic differences during walking in patients with and without symptomatic femoroacetabular impingement, *Clin. Biomech.* 28 (2013), <https://doi.org/10.1016/j.clinbiomech.2013.05.002>.
- L.E. Diamond, T.V. Wrigley, K.L. Bennell, R.S. Hinman, J. O'Donnell, P.W. Hodges, Hip joint biomechanics during gait in people with and without symptomatic femoroacetabular impingement, *Gait Posture* 43 (2016) 198–203, <https://doi.org/10.1016/j.gaitpost.2015.09.023>.
- M.J. Kennedy, M. Lamontagne, P.E. Beaulé, Femoroacetabular impingement alters hip and pelvic biomechanics during gait: walking biomechanics of FAI, *Gait Posture* 30 (2009) 41–44, <https://doi.org/10.1016/j.gaitpost.2009.02.008>.
- J.H. Rylander, B. Shu, T.P. Andriacchi, M.R. Safran, Preoperative and postoperative sagittal plane hip kinematics in patients with femoroacetabular impingement during level walking, *Am. J. Sports Med.* 39 (2011) 36S–42S, <https://doi.org/10.1177/0363546511413993>.
- M. Lamontagne, M.J. Kennedy, P.E. Beaulé, The effect of cam FAI on hip and pelvic motion during maximum squat, *Clin. Orthop. Relat. Res.* 467 (2009) 645–650, <https://doi.org/10.1007/s11999-008-0620-x>.
- J.J. Bagwell, J. Snibbe, M. Gerhardt, C.M. Powers, Hip kinematics and kinetics in persons with and without cam femoroacetabular impingement during a deep squat task, *Clin. Biomech.* 31 (2016) 87–92, <https://doi.org/10.1016/j.clinbiomech.2015.09.016>.
- L.E. Diamond, K.L. Bennell, T.V. Wrigley, R.S. Hinman, J. O'Donnell, P.W. Hodges, Squatting biomechanics in individuals with symptomatic femoroacetabular impingement, *Med. Sci. Sports Exerc.* 49 (2017) 1520–1529, <https://doi.org/10.1249/MSS.0000000000001282>.
- J. Rylander, B. Shu, J. Favre, M. Safran, T. Andriacchi, Functional testing provides unique insights into the pathomechanics of femoroacetabular impingement and an objective basis for evaluating treatment outcome, *J. Orthop. Res.* 31 (2013) 1461–1468, <https://doi.org/10.1002/jor.22375>.
- L.E. Diamond, K.L. Bennell, T.V. Wrigley, R.S. Hinman, M. Hall, J. O'Donnell, P.W. Hodges, Trunk, pelvis and hip biomechanics in individuals with femoroacetabular impingement syndrome: strategies for step ascent, *Gait Posture* (2018), <https://doi.org/10.1016/j.gaitpost.2018.01.005>.
- N.C. Casartelli, N.A. Maffiuletti, J.F. Item-Glatthorn, S. Staehli, M. Bizzini, F.M. Impellizzeri, M. Leunig, Hip muscle weakness in patients with symptomatic femoroacetabular impingement, *Osteoarthr. Cartil.* 19 (2011) 816–821, <https://doi.org/10.1016/j.joca.2011.04.001>.
- S. Kierkegaard, I. Mechlenburg, B. Lund, K. Søballe, U. Dalgas, Impaired hip muscle strength in patients with femoroacetabular impingement syndrome, *J. Sci. Med. Sport* 20 (2017) 1062–1067, <https://doi.org/10.1016/j.jsams.2017.05.008>.
- D.S. Catelli, E. Kowalski, P.E. Beaulé, K. Smit, M. Lamontagne, Asymptomatic individuals with femoroacetabular deformity demonstrate stronger hip extensors and greater pelvis mobility during the deep squat task, *Orthop. J. Sport. Med.* 6 (2018) 1–10, <https://doi.org/10.1177/2325967118782484>.
- L.E. Diamond, T.V. Wrigley, R.S. Hinman, P.W. Hodges, J. O'Donnell, A. Takla, K.L. Bennell, Isometric and isokinetic hip strength and agonist/antagonist ratios in symptomatic femoroacetabular impingement, *J. Sci. Med. Sport* 19 (2016) 696–701, <https://doi.org/10.1016/j.jsams.2015.10.002>.
- K.C.G. Ng, G. Mantovani, L. Modenese, P.E. Beaulé, M. Lamontagne, Altered walking and muscle patterns reduce hip contact forces in individuals with symptomatic cam femoroacetabular impingement, *Am. J. Sports Med.* 46 (2018) 2615–2623, <https://doi.org/10.1177/0363546518787518>.
- F. Malagelada, V.A. Del Carmen, S.J. Barke, L. Guirao Cano, E. Pleguezuelos Cobo, The anterior mini-open approach for femoroacetabular impingement: gait and functional assessment at one year post-surgery, *Ann. Phys. Rehabil. Med.* 58 (2015) 60–65, <https://doi.org/10.1016/j.rehab.2014.09.013>.
- N. Brisson, M. Lamontagne, M.J. Kennedy, P.E. Beaulé, The effects of cam femoroacetabular impingement corrective surgery on lower-extremity gait biomechanics, *Gait Posture* 37 (2013) 258–263, <https://doi.org/10.1016/j.gaitpost.2012.07.016>.
- H. Nötzli, T. Wyss, C. Stoecklin, M. Schmid, K. Treiber, J. Hodler, The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement: commentary, *J. Bone Jt. Surg.* 84 (2002) 556–560, <https://doi.org/10.1024/0369-8394.92.11.475>.
- K.S. Rakhra, A.M. Sheikh, D. Allen, P.E. Beaulé, Comparison of MRI alpha angle measurement planes in femoroacetabular impingement, *Clin. Orthop. Relat. Res.* 467 (2009) 660–665, <https://doi.org/10.1007/s11999-008-0627-3>.
- G. Mantovani, M. Lamontagne, How different marker sets affect joint angles in inverse kinematics framework, *J. Biomech. Eng.* 139 (2017) 044503, <https://doi.org/10.1115/1.4034708>.
- A. Rajagopal, C.L. Dembia, M.S. DeMers, D.D. Delp, J.L. Hicks, S.L. Delp, Full body musculoskeletal model for muscle-driven simulation of human gait, *IEEE Trans. Biomed. Eng.* 9294 (2016) 1, <https://doi.org/10.1109/TBME.2016.2586891>.
- S.L. Delp, F.C. Anderson, A.S. Arnold, P. Loan, A. Habib, C.T. John, E. Guendelman, D.G. Thelen, OpenSim: open-source software to create and analyze dynamic simulations of movement, *IEEE Trans. Biomed. Eng.* 54 (2007) 1940–1950, <https://doi.org/10.1109/TBME.2007.901024>.
- A. Mantoan, C. Pizzolato, M. Sartori, Z. Sawacha, C. Cobelli, M. Reggiani, MOTO-NMS: a MATLAB toolbox to process motion data for neuromusculoskeletal modeling and simulation, *Source Code Biol. Med.* 10 (2015) 12, <https://doi.org/10.1186/s13029-015-0044-4>.
- M. Lamontagne, N. Brisson, M.J. Kennedy, P.E. Beaulé, Preoperative and post-operative lower-extremity joint and pelvic kinematics during maximal squatting of patients with cam femoroacetabular impingement, *J. Bone Jt. Surg.* 93 (2011) 40–45, <https://doi.org/10.2106/JBJS.J.01809>.
- K.C.G. Ng, H. El Daou, M.J.K. Banks, F. Rodriguez y Baena, J.R.T. Jeffers, Hip joint torsional loading before and after cam femoroacetabular impingement surgery, *Am. J. Sports Med.* 47 (2019) 420–430, <https://doi.org/10.1177/0363546518815159>.
- S. Chegini, M. Beck, S.J. Ferguson, The effects of impingement and dysplasia on stress distributions in the hip joint during sitting and walking: a finite element analysis, *J. Orthop. Res.* 27 (2009) 195–201, <https://doi.org/10.1002/jor.20747>.
- K.L. Bennell, L. Spiers, A. Takla, J. O'Donnell, J. Kasza, D.J. Hunter, R.S. Hinman, Efficacy of adding a physiotherapy rehabilitation programme to arthroscopic management of femoroacetabular impingement syndrome: A randomised controlled trial (FAIR), *BMJ Open* 7 (2017), <https://doi.org/10.1136/bmjopen-2016-014658>.
- C.L. Lewis, S.A. Sahrman, D.W. Moran, Effect of position and alteration in

- synergist muscle force contribution on hip forces when performing hip strengthening exercises, *Clin. Biomech.* 24 (2009) 35–42, <https://doi.org/10.1016/j.clinbiomech.2008.09.006>.
- [40] P. Malloy, A.V. Stone, K.N. Kunze, W.H. Neal, E.C. Beck, S.J. Nho, Patients with unilateral femoroacetabular impingement syndrome have asymmetrical hip muscle cross-sectional area and compensatory muscle changes associated with preoperative pain level, *Arthroscopy* 35 (2019) 1445–1453, <https://doi.org/10.1016/j.arthro.2018.11.053>.
- [41] N.C. Casartelli, N.A. Maffioletti, J.F. Item-Glatthorn, F.M. Impellizzeri, M. Leunig, Hip muscle strength recovery after hip arthroscopy in a series of patients with symptomatic femoroacetabular impingement, *Hip Int.* 24 (2014) 387–393, <https://doi.org/10.5301/hipint.5000131>.
- [42] D.S. Catelli, M. Wesseling, I. Jonkers, M. Lamontagne, A musculoskeletal model customized for squatting task, *Comput. Methods Biomech. Biomed. Eng.* 22 (2019) 21–24, <https://doi.org/10.1080/10255842.2018.1523396>.
- [43] L. Modenese, A.T.M. Phillips, Prediction of hip contact forces and muscle activations during walking at different speeds, *Multibody Syst. Dyn.* 28 (2012) 157–168, <https://doi.org/10.1007/s11044-011-9274-7>.