Title: Hip Muscle Forces and Contact Loading during Squatting After Cam FAI Surgery

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ABSTRACT

Background: Corrective hip surgery for cam-type femoroacetabular impingement (FAI) aims to improve hip function and prevent joint degeneration. The purpose was to compare muscle and hip contact forces (HCF) during squatting in cam-FAI patients before and after hip corrective surgery, and in healthy control participants (CTRL).

Methods: Ten symptomatic cam-FAI male patients performed deep squatting pre- and at 2 years postoperatively. Patients were age, and body-mass-index matched to 10 CTRL male participants. Full-body kinematics and kinetics were computed and, muscle forces and HCF were estimated using musculoskeletal model and static optimization. Normalized squat cycle ($\%_{SC}$) trials were compared using statistical non-parametric mapping (SnPM).

Results: Postoperative patients squatted down with higher anterior pelvic tilt (11-29$\%_{SC}$, P=.004), higher hip flexion (9-31$\%_{SC}$, P=.003) and greater hip extension moments (21-26$\%_{SC}$, P=.008) compared to preoperative FAI. Preoperative patients also demonstrated lower anterior pelvic tilt (7-9$\%_{SC}$, P=.023; 92-99$\%_{SC}$, P=.016) and lower hip flexion (87-97$\%_{SC}$, P=.008) compared to the CTRL. Postoperative patients showed increased semimembranosus force concerning their preoperative values (68-73$\%_{SC}$, P=.002). Preoperative forces were also lower than the CTRL for the adductor magnus (28-34$\%_{SC}$, P=.011), psoas major (49-58$\%_{SC}$, P=.023) and semimembranosus (0-14$\%_{SC}$, P=.001; 33-44$\%_{SC}$, P=.004; 67-75$\%_{SC}$, P=.006; 92-100$\%_{SC}$, P=.003); however, preoperative patients showed greater inferior gluteus maximus forces (34-67$\%_{SC}$, P=.001) than the CTRL, whereas the postoperative did not differ from the CTRL. Higher posterior (77-81$\%_{SC}$, P=.009), superior (67-71$\%_{SC}$, P=.004) and resultant HCF magnitude (67-

71%$_{SC}$, *P*=.004) were identified postoperatively in comparison to the preoperative. Preoperative posterior HCF was also lower than the CTRL (0-7%$_{SC}$, *P*=.005; 73-79%$_{SC}$, *P*=.006), whereas the postoperative did not differ from the CTRL.

Conclusions: Higher postoperative anterior pelvic tilt was associated with an indication of returning closer to normal pelvic motion, resembling the CTRL data. Lower preoperative anterior pelvic tilt was associated with muscle force imbalance indicated by decreased semimembranosus and increased gluteus maximus forces. The overall increased postoperatively muscle forces were associated with improved pelvis mobility and HCF increase to the CTRL standards.

Clinical Relevance: Muscle forces and HCF may be indicative of postoperative joint health restoration and alleviated symptoms.

1. INTRODUCTION

Surgical correction of the cam morphology has become a very common procedure in orthopaedics[1], providing improved clinical function and quality of life in patients with symptomatic femoroacetabular impingement (FAI)[2–6]. Although a high percentage of the general population have cam morphology[7], the majority will go on through their life with minimal symptoms[8], cam morphology has been associated with acetabular cartilage damage[9–13] and is a known risk factor for hip osteoarthritis (OA)[14–16].

Patients with cam-FAI demonstrate altered gait[17–21], squatting[22–26], and stair climbing[27,28] biomechanics, indicating reduced hip and pelvic range of motion (ROM), and reduced hip flexion and external rotation moments compared to healthy controls. Besides, neuromuscular adaptations have been reported to influence symptoms and contribute to changes in biomechanical outcomes[19,29–32]. Although several studies reported on hip biomechanics in patients from pre-arthritic hip disease [20,27,33–37], the effect on musculoskeletal loading in terms of the dynamic muscle forces and hip contact force (HCF) is still limited to gait[32,37,38] with little information during functional ROM. As osteochondroplasty of the cam morphology can decrease joint contact loading by 21-27%[39,40], a further understanding of changes in muscle forces and their consequent effect on joint loading may provide benefits to design better pre- and/or postoperative FAI rehabilitation programs after corrective FAI surgery[41,42]. Therefore, the purpose of this study was to (1) compare muscle force contributions and hip contact forces in cam FAI patients before and after surgical correction during deep squatting task, (2) compare the results with the ones obtained by healthy control participants (CTRL).

2. MATERIALS AND METHODS

2.1. Participants

Eighteen male patients were initially recruited from the surgeon's practice, presenting unilateral clinical signs of hip pain and positive impingement tests, however only twelve of them returned to the laboratory for the postoperative biomechanical assessment, and two of them were removed from the analysis due to obesity (> 30 kg/m^2) and technical issues (i.e. absence of ground reaction force data). They were age- and BMI-matched to 10 male CTRL participants of our healthy individuals' database who had normal morphological hips and have no history of hip pain (Table 1). The FAI patients and CTRL participants underwent pelvic and knee CT imaging (Acquilion, Toshiba Medical Systems Corporation, JAP; or Discover CT750, GE Healthcare, CAN), to confirm the presence/absence of the cam morphology – i.e. axial (3:00) and/or radial (1:30) alpha angle larger than 50.5° and 60°, respectively[15,43,44]. The participants were then transferred to the local university where they completed the Hip Disability and Osteoarthritis Outcome Score (HOOS) questionnaire and performed the motion analysis protocol. Surgical correction (e.g. osteochondroplasty and labral-chondral debridement) was performed by the same senior surgeon via an open dislocation with an anterior approach (n = 3) or mini-open/arthroscopy approach (n = 7) – Table A.1 (Appendix). After surgery, the surgical staff recommended isometric exercises for the glutei and quadriceps to the patients on their own for the first six weeks following the surgery. Then, it was recommended that they sought physiotherapist care for another four to six weeks (two to three times a week) in order to perform active ROM exercises, as well as muscle strengthening against gravity, muscle resistance and gait training. This study did not control surgical aftercare. The same preoperatively motion analysis protocol was performed 2-years postoperatively (25.2 ± 1.1 months) on the FAI patients, and once on the CTRL participants. Exclusion criteria consisted of any other lower limb hip dysmorphia, severe history of traumas or surgeries, or a body mass index (BMI) indicating obesity.

This study used a subset of participants enrolled in other studies[36,38], and the main surgical findings are reported in Beaulé et al. (2017)[6]. The study was approved by the hospital's and university's research ethics boards and all participants provided written informed consent for participation.

2.2. Motion Analysis

Participants were instructed to warm up on a cycle ergometer for 5 minutes, perform uninstructed stretching, and completed 3 trials of the sit-and-reach flexibility test while barefoot[45]. Forty-five retro-reflective markers were placed on the participants according to the University of Ottawa Motion Analysis Model (UOMAM) marker set[46]. Five deep squatting trials were performed at a self-selected pace, with the feet positioned parallel, hip-width apart and the arms stretched out anteriorly. The marker trajectories were captured using a ten-camera infrared system sampled at 200 Hz (Vicon MX-13, VICON, UK) and ground reaction forces (GRF) were captured using two embedded force plates sampled at 1000 Hz (FP4060-08, Bertec Corporation, USA), with each participant's foot on each of the two force plates. The data were labelled and filtered (zero-lag, 4^{th} order Butterworth at 6Hz) using Nexus 2.6.1 (VICON, UK). The statistical analyses were performed over the full squat cycle (defined by the maximum hip extension point – standing – and lowest depth point – squatted – during descending and ascending phases combined) and all variables were time-normalized to its cycle.

2.3. Musculoskeletal Modelling

A newly-tuned musculoskeletal model (MSKM), based on a previous generic MSKM[47,48] and specifically adapted for high hip and knee flexion ranges[49], containing 80 lower-limb Hill-type muscle-tendon units (MTU) with 37 degrees of freedom (DoF), was used in an open-source musculoskeletal simulation software (OpenSim™ 3.3, Stanford University, Stanford, USA)[50].

The marker trajectories and GRF dataset were prepared to OpenSim file format[51] and the models were scaled based on each patient's static anthropometric dimensions. The markers on the left and right anterior superior and posterior superior iliac spines (ASIS and PSIS), as well as the left and right medial and lateral knee epicondyles, were defined according to their placement during CT scanning, therefore pelvis and knee markers had a ten-time higher non-isotropic scaling weight. Inverse kinematics and inverse dynamics tools were used to compute joint angles and net joint moments for each degree of freedom, while the static optimization tool was used to compute muscle forces while minimizing the sum of squared muscle activation. An optimal force of 10 N was defined for the reserve actuators for the three hip coordinates to avoid muscle forces saturation during static optimization calculations. The *JointReaction* analysis tool calculated HCF as three-dimensional vectors acting on the acetabulum expressed in the femoral coordinate system. The hip muscle forces, each HCF component (i.e. x: anterior-posterior, y: superior-inferior, z: medial-lateral) and resultant magnitude were normalized to bodyweight (BW) and were selected as variables, along with the HCF vector direction on the sagittal and frontal planes – Figure 1.

FIGURE 1

2.4. Data analysis

Squat speed execution was determined on both descent and ascent phases separately. Squat depth was calculated based on the height of the center of the pelvis at its lowest point of the squat cycle, and the maximum squat depth is reported as a percentage of leg length (measured from the affected anterior superior iliac spine to the medial malleolus), with a value of 0% representing a maximum squat. Data from the five trials performed per patient were averaged and only the affected (surgical) side was analyzed. Kinematic ROM was assessed for both pelvis and hip joints.

A Statistical non-Parametric Mapping (SnPM)[52] two-tail paired Wilcoxon signed-rank test (between the pre- and post-op) and Mann-Whitney U test (for the control comparisons) were performed to compare the kinematics, kinetics, muscle forces and the HCF outputs ($P = .05$) in the time-normalized (0-100%) full squat cycle ($\%_{SC}$) data conditions. This statistical analysis considers the entire waveform data and therefore does not correct for differences in movement speed. The SnPM{t} representing the non-parametric univariate pseudo-t-statistic was calculated at each point of the waveform, and if it exceeded the critical threshold t, the difference between groups was considered significant in that part of the waveform. Although all affected 40 MTUs were processed, only the hip MTUs that presented a force higher than 0.5 BW were analyzed.

The demographics and the discrete data were assessed for normality using the Shapiro-Wilk test and paired t-test analyses or one-way ANOVA, followed by post hoc comparisons using Bonferroni corrections, were performed ($P = .05$). All analyses were performed in a custom Matlab script (v. R2018b, MathWorks Inc, Natick, USA).

3. RESULTS

3.1. Demographics and Patient-Reported Outcome Measures

Postoperative patients showed improvements in all five HOOS categories, and their follow-up BMI was unchanged (Table 1). Postoperative scores were significantly lower than the CTRL values in four out of the five HOOS sub-categories: Symptoms, Pain, Sports and Recreational Activities, and Quality of Life.

3.2. Squat parameters

No differences on squatting speed were found between pre- (descent: 0.27 ± 0.14 m/s, ascent: 0.30 ± 0.14 m/s), postoperative (descent: 0.24 ± 0.06 m/s, ascent: 0.30 ± 0.08 m/s) and CTRL (descent: 0.29 ± 0.09 m/s, ascent: 0.36 ± 0.10 m/s) on both phases of the squat (P = .66 and P = .39, respectively). Also, no differences in squat depth, represented in percentage of leg length, were detected among the groups (preoperative: 30.5% ± 8.9; postoperative: 31.3% ± 13.4; CTRL: 28.1% ± 14.3, P = .41).

3.3. Kinematics & Kinetics

Patients showed an increase in anterior pelvic tilt postoperatively during squat decent (from 11 to $29\%_{SC}$ (P = .004). Preoperative anterior pelvic tilt was also significantly lower than the CTRL at 7-9% and $92\text{-}99\%_{SC}$ (P = .023 and P = .016, respectively). Preoperative patients also showed lower hip flexion compared to postoperative FAI ($9\text{-}31\%_{SC,}$ P = .003) and CTRL ($87\text{-}97\%_{SC,}$ P = .008) groups. No significant differences in pelvic tilt and hip flexion were found between postoperative and CTRL kinematics (P > .05). Also, no differences in the hip abduction were found among the groups – Figure 2.

Discrete analysis of total ROM for pelvic tilt and hip sagittal, frontal and transverse planes also did not show significant differences among the groups – Table 2.

FIGURE 2

Hip kinetic analysis showed significantly lower hip extension moment preoperatively compared to their postoperative values during squat descent (21-26%$_{SC}$, P = .008). In FAI patients an increased hip flexion moment at the end of the squat cycle, compared to the CTRL group, persisted postoperatively (87-100%$_{SC}$, P = .001). No significant differences in the hip frontal moment were found among the groups – Figure 3.

FIGURE 3

3.4. Muscle Forces

No significant muscle forces differences were found between preoperative and postoperative FAI patients, except for the semimembranosus, in which the force was increased from 63 to 73%$_{SC}$ postoperatively (P = .002). Preoperative forces were lower than the CTRL for the adductor magnus (28-34%$_{SC}$, P = .011), psoas major (49-58%$_{SC}$, P = .023) and semimembranosus (0-14%$_{SC,}$ 33-44%$_{SC,}$ 67-75%$_{SC}$, and 92-100%$_{SC}$, P < .01). However, the preoperative FAI patients showed greater forces than the CTRL for the inferior portion of the gluteus maximus (34-67%$_{SC}$, P = .001), where the postoperative values did not differ from the CTRL. Six hip muscles had a peak force higher than 0.5 BW and were plotted in Figure 4.

FIGURE 4

3.5. Hip Contact Forces

Lower posterior (77-81%$_{SC}$, P=.009), superior (67-71%$_{SC}$, P=.004), as well as the total HCF magnitude (67-71%$_{SC}$, P=.004), were observed preoperatively in comparison to the postoperative values. Preoperative posterior HCF was also lower than the CTRL (0-7%$_{SC}$, P=.005 and 73-79%$_{SC}$, P=.006), whereas the postoperative values did not differ from the CTRL standards – Figures 5. Sagittal and frontal planes HCF vector directions did not show any statistical difference during the squat among the groups.

FIGURE 5

4. DISCUSSION

To our knowledge, this is the first study that examined hip muscle and contact force estimations before and after cam-type FAI surgery during a deep squatting task using musculoskeletal modelling FAI. Our findings show that the HCF reached a magnitude of 3 BW load at the deepest phase of the squat, with the rectus femoris, adductor magnus, glutei and hamstrings being the main muscle contributors to the task performance. Although postoperative FAI patients did not improve their squat depth, they showed altered squat kinematics, with increased anterior pelvic tilt and hip flexion during the descending phase of the squat, as well as greater hip extension moments during squat descent. These have been associated with a restoration of a muscle force imbalance presented preoperatively, where preoperative FAI patients had higher gluteus maximus and lower semimembranosus forces compared to the other groups.

Postoperative patients demonstrated higher anterior tilt during the full squat cycle, perhaps indicating an ability to return their pelvis to a more (innate) anteriorly tilted position, therefore, resembling the CTRL group[53]. Ultimately, considering the anterior-superior location of the cam morphology in the femoral head[8] is susceptible to impinge when the pelvis is anteriorly tilted[54], the FAI patients had possibly, the pelvis anteriorly tilted in their native position. However, with the development of the cam and the further onset of the symptomatology may have caused them to adopt a more posteriorly tilted pelvic position, as well as limiting their hip mobility as a protective mechanism to reduce HCF[32,38]. Previous study indicated decreased pelvic ROM during squat in preoperative FAI compared to CTRL[22] but no significant improvements postoperatively[34]. Conversely, these studies[22,34] showed a kinematic restoration of the pelvis to a neutral position at the deepest squat point, that was not reached by our cohort. The difference in the studies cohort may have an effect, in which ours consisted exclusively of males whereas they had a mixed composition and were also slightly younger. Additionally, our CTRL participants demonstrated peculiarly poor performance at the sit-and-reach flexibility test (Table 1), which could also justify their inability to reach a neutral pelvic position at the bottom of the squat as expected. Especially considering that spinopelvic stiffness can be an influencing factor of FAI symptomatology[53,55].

Preoperative FAI showed significantly lower semimembranosus, adductor magnus and psoas major forces compared to the CTRL group during a great part of the squat cycle; which was also combined with greater forces performed by the inferior portion of the gluteus maximus. Specifically, the semimembranosus will act synergistically along with the gluteus maximus towards favoring the posterior pelvic tilt preventing the impingement. These two muscles combined with the action of the other extensor muscles will dynamically stabilize the pelvis especially at mid and full depth of the squat task. Therefore, we can speculate that reduced semimembranosus force preoperatively was compensated by a greater contraction of the gluteus maximus, perhaps as a protective mechanism as the hip descents towards the impingement position[26]. Postoperatively the increase of semimembranosus and decrease of gluteus maximus forces contributed to the pelvis stabilization comparable to the CTRL group. The bi-articular semimembranosus acts to overcome the bodyweight load and extend the hip. Increased activation of the other synergist medial hamstring, the semitendinosus, was already explored postoperatively during squat descent[36]. However, the postoperative increase of the semimembranosus force only reached significance in the ascending phase of the squat, as perhaps during the descending phase, the static optimization approach may not have perfectly expressed the eccentric mechanisms that were altered by the joint pathology. Still, CTRL participants demonstrated a load preference towards the semimembranosus over the biceps femoris, which was the opposite for pre- and postoperative FAI, and can be further investigated in future studies. **The findings related to the muscle force distributions, associated with the minimal changes in kinematics may evidence that the muscles are the contributors of change in the progression of FAI syndrome.**

The increased overall postoperative muscle forces, especially at the time-point of the where the semimembranosus reached significant higher forces, can be associated with the increase in the magnitude of its resultant HCF[56]. The squat is a task with naturally higher ROM, and its joint ranges are not necessarily associated with larger ground reaction forces (that would likely reflect joint reaction loading). Therefore although previous studies on gait[32,38] reported a decrease in HCF had been linked with decreased bone mineral joint density[57] or improved T1rho signal associated with better cartilage health[6,37], the higher muscle forces and HCF in the present study can be the initial evidence of postoperative joint health restoration and alleviated symptoms. In this line, finite element analysis would be able to translate HCF to shear stresses providing a clearer picture of the pathomechanism.

There are some limitations to this study that should be addressed. First, we acknowledge the small sample size of our cohort, increasing the number of participants would result in higher predictive power. As our patients were all male and had cam-only FAI morphology (no pincer or mixed), the inference from our findings is limited to this population. Second, **we acknowledge that the surgical choices for FAI treatment have evolved in the last few years, and while arthroscopic osteochondroplasty has been widely used nowadays** our cohort consisted of patients that underwent primary surgical dislocation or mini-open approaches. Although functional[58] and patient-reported outcomes[59] were similar, the effect of both surgeries could affect the muscle characteristics Third, the static optimization method to calculate muscle forces may under-estimate co-contraction mechanisms altered by a joint pathology; however, this technique still produces results closest to experimental HCF[56]. Fourth, the cam morphology has not been directly parameterized in the musculoskeletal model as scaled generic models were used, which might have influenced hip contact forces outputs.

Suggestions for future studies may include: i) subject-specific cam-type hip bone morphology, to visualize intersubject pre- and postoperative effects of the surgical intervention during loaded dynamic motion; and ii) a controlled clinical trial with conservative management of FAI pain, which can test if any gain in pelvic mobility may also generate increased muscle force before performing the surgical correction.

This study provided insights into muscle and hip contact forces after surgical correction of cam morphology and postoperative rehabilitation at a short/mid-term follow-up. Although no squat depth differences were found among the groups, the lack of anterior pelvic tilt shown by the preoperative FAI was associated with the muscle force imbalance presenting higher contraction of the gluteus maximus but the reduced contraction of the semimembranosus after hip osteochondroplasty. **This can be evidence that the muscle contraction patterns are precursors of motion changes in FAI syndrome.** Postoperative hip flexion and anterior pelvic tilt increase are indicative of returning closer to normal pelvic motion, resembling the CTRL data. Finally, the overall increased postoperative muscle forces, associated with increased pelvic mobility, increased the HCF to CTRL standards.

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Figure 1. Three-dimensional HCF vector directions were expressed in the femoral coordinate system along the anterior-posterior (x), superior-inferior (y) and medial-lateral (z) axis, and in the sagittal (φ) and frontal (θ) planes.

Figure 2. Pelvic tilt, hip sagittal and hip frontal kinematics during squatting task, for the FAIS preoperative (red), postoperative (blue) and CTRL (black) conditions. SnPM results are displayed below the figure and indicate significant ($P < .05$) differences between (a) FAI pre vs FAI post, (b) FAI pre vs CTRL, and (c) FAI post vs CTRL.

Figure 3. Hip sagittal and hip frontal kinetics during squatting task, for the FAIS preoperative (red), postoperative (blue) and CTRL (black) conditions. SnPM results are displayed below the figure and indicate significant ($P < .05$) differences between (a) FAI pre vs FAI post, (b) FAI pre vs CTRL, and (c) FAI post vs CTRL.

Figure 4. Muscle forces during the squatting task, for the FAIS preoperative (red), postoperative (blue) and CTRL (black) conditions. Muscle forces were normalized by body weight (BW) and determined from static optimization. SnPM results are displayed below the figure and indicate significant ($P < .05$) differences between (a) FAI pre vs FAI post, (b) FAI pre vs CTRL, and (c) FAI post vs CTRL.

Figure 5. Hip contact forces during squatting task, for the FAIS preoperative (red), postoperative (blue) and CTRL (black) conditions in all three planes and the resultant magnitude forces. SnPM

results are displayed below the figure and indicate significant (P < .05) differences between (a) FAI pre vs FAI post, (b) FAI pre vs CTRL, and (c) FAI post vs CTRL.

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Table 1

Table 1. Summary of demographics, flexibility test, cam morphology measurement of the affected hips, and pain questionnaire, reporting mean ± SD.

Parameter		FAI pre	FAI post	CTRL	*P* value		
					pre vs post	pre vs CTRL	post vs CTRL
Participants (n)		10		10			
Age (years)		35 ± 8	37 ± 8	34 ± 7		.90	.46
BMI (kg/m^2)		26 ± 3	26 ± 4	25 ± 3	.87	.87	.77
Flexibility Test (cm)		30 ± 7	26 ± 9	20 ± 11	.08	.06	.28
alpha-angle (deg)	3:00 position	54 ± 8	44 ± 2	43 ± 3	<.01	<.01	.91
	1:30 position	66 ± 5	50 ± 7	53 ± 4	<.01	<.01	.27
HOOS	Symptoms	71 ± 11	82 ± 10	99 ± 2	.02	<.01	<.01
	Pain	71 ± 17	91 ± 6	98 ± 5	<.01	<.01	<.01
	Activities of Daily Living	81 ± 15	97 ± 2	99 ± 2	.02	<.01	.07
	Sports & Recreational Activities	57 ± 26	87 ± 14	96 ± 8	.01	<.01	.04
	Quality of Life	39 ± 23	67 ± 22	94 ± 13	.01	<.01	<.01

Table 2. Summary of pelvis and hip kinematics range of motion (ROM) during deep squating, reporting mean ± SD.

Kinematics ROM	FAI pre	FAI post	CTRL	*P* value		
				pre vs post	pre vs CTRL	post vs CTRL
Pelvic Tilt	24 ± 7	26 ± 7	24 ± 10	.55	.91	.56
Hip Sagittal	113 ± 12	113 ± 13	111 ± 12	.98	.76	.80
Hip Frontal	12 ± 4	11 ± 3	10 ± 4	.82	.44	.51
Hip Transverse	25 ± 10	23 ± 7	24 ± 7	.68	.91	.75

Figure 1

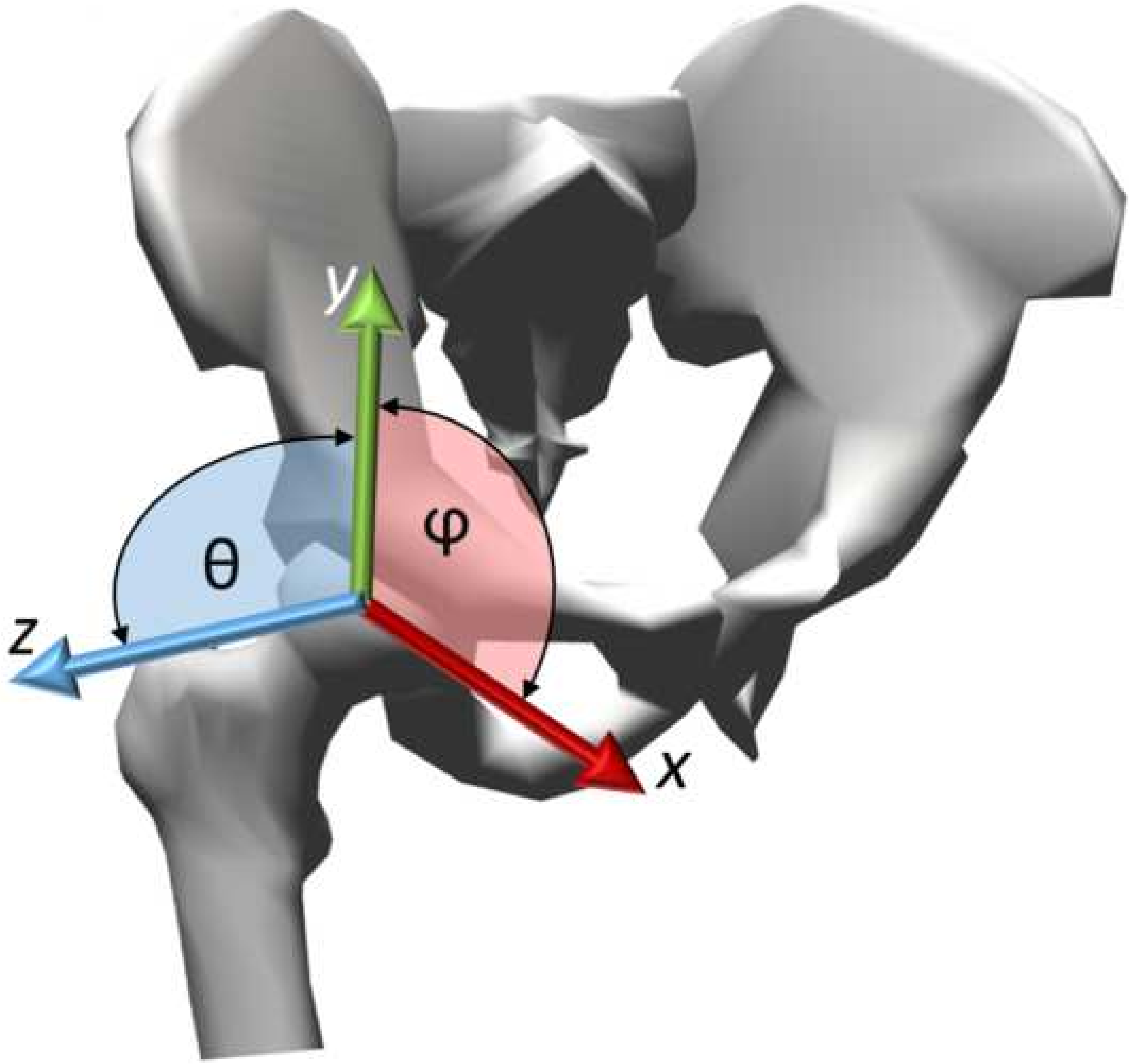


Figure 2

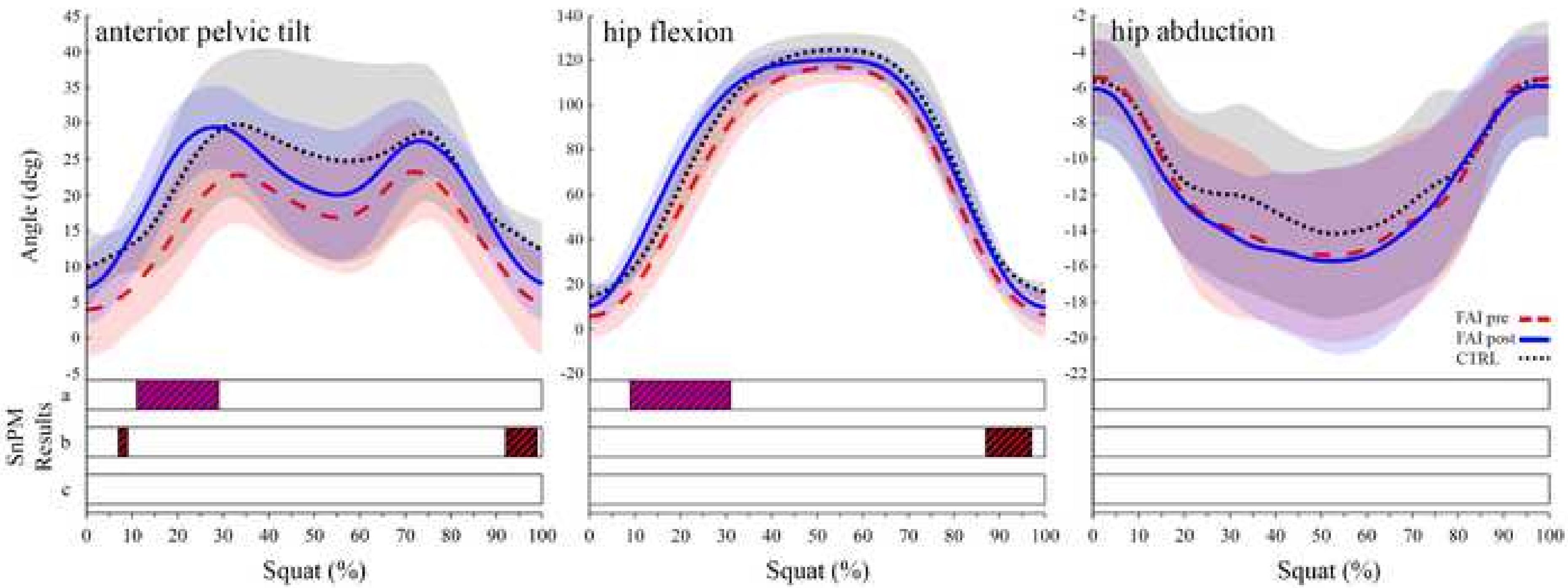

anterior pelvic tilt
hip flexion
hip abduction
Angle (deg)
SnPM Results
a
b
c
Squat (%)
Squat (%)
Squat (%)
FAI pre
FAI post
CTRL

Figure 3

Click here to access/download;Figure;Figure 3.tif

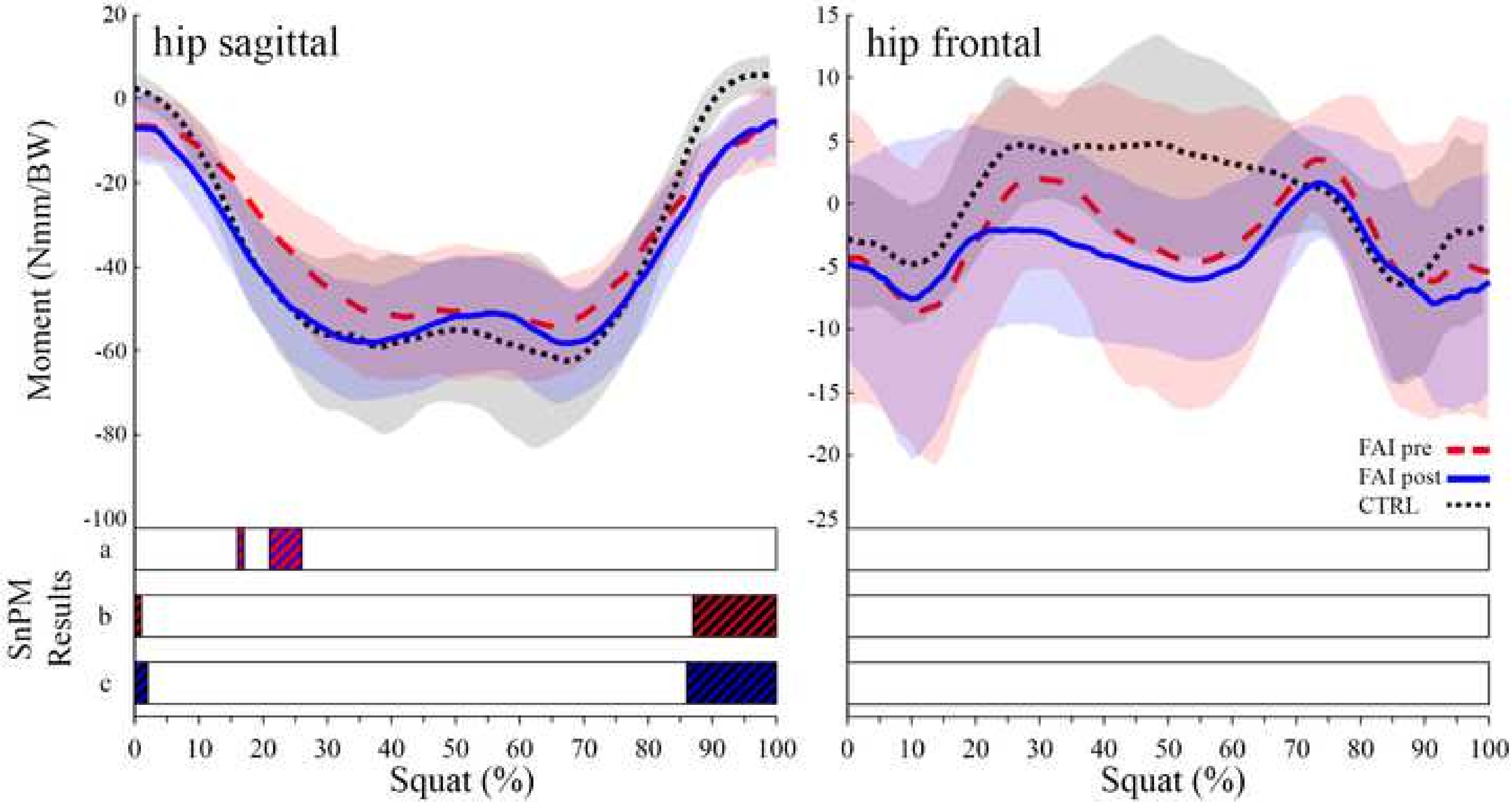


Figure 4

Click here to access/download;Figure;Figure 4.tif

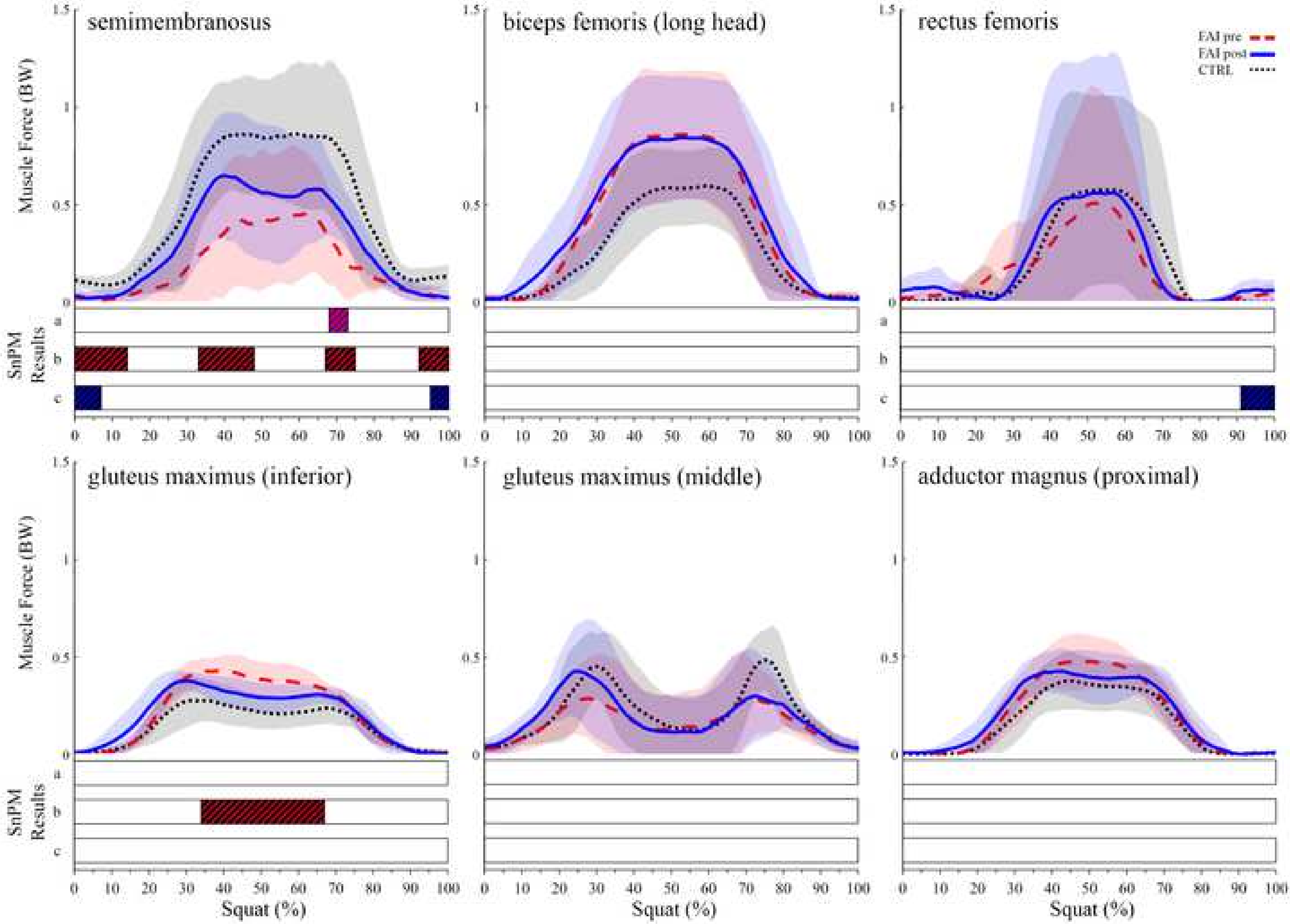
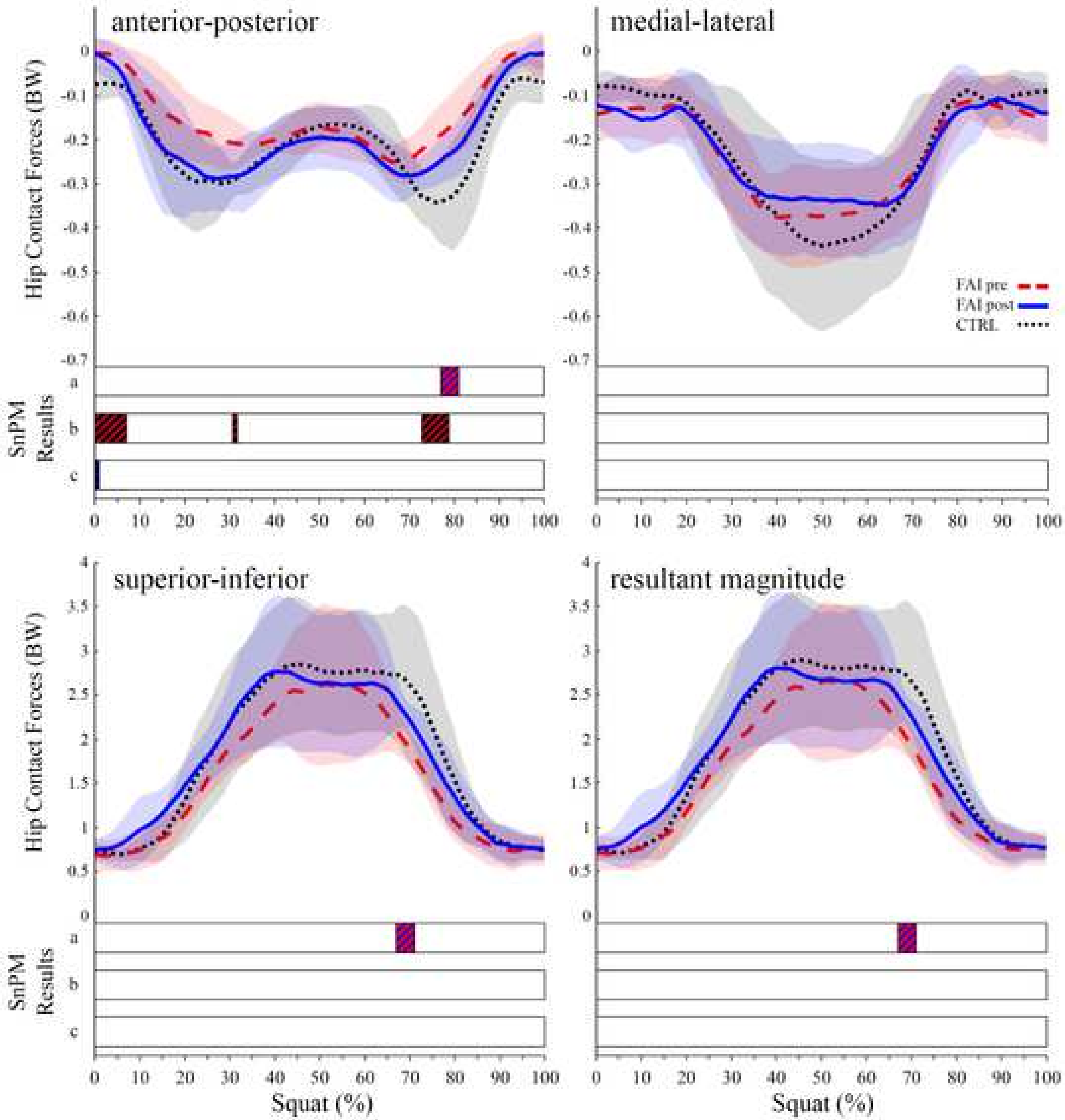


Figure 5



anterior-posterior
medial-lateral
superior-inferior
resultant magnitude
Hip Contact Forces (BW)
SnPM Results
a
b
c
FAI pre
FAI post
CTRL
Squat (%)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0.5
1
1.5
2
2.5
3
3.5
4
0 10 20 30 40 50 60 70 80 90 100

Table A1

Table A.1. Radiograph and Surgical Details of the 10 Cam FAI Patients (5 Left and 5 Right Hips).

Alpha Angle (º)				Surgical Approach	Cartilage Damage	Procedure
Preoperative		Postoperative				
3:00 Axial	1:30 Radial	3:00 Axial	1:30 Radial			
62	57	47	44	Surgical dislocation	Beck 4	Labral-chondral debridement
47	72	45	47	Surgical dislocation	Beck 4, 5	Labral-chondral debridement and restabilization with anchor
48	61	*	*	Surgical dislocation	Beck 4	Labral-chondral debridement and restabilization with anchor
64	68	42	65	Arthroscopy/mini-open	Beck 4	Labral-chondral debridement
49	63	45	51	Arthroscopy/mini-open	Beck 4	Labral-chondral debridement
67	74	44	47	Arthroscopy/mini-open	Beck 4	Labral-chondral debridement
47	63	42	51	Arthroscopy/mini-open	Beck 4	Labral-chondral debridement and restabilization with anchor
53	64	42	57	Arthroscopy/mini-open	Beck 4	Labral-chondral debridement
46	70	40	45	Arthroscopy only	Beck 4	Labral-chondral debridement and restabilization with anchor
53	64	47	47	Arthroscopy only	Beck 4	Labral-chondral debridement

* patient did not come back for a postoperative CTscan

Note: The average age at the time of surgery was 34.6 years (range, 23.1 to 46.4 years), and the average body mass index (BMI) was 26.66±4.79 kg/m^2. All patients had a chondro-osteoplasty of the femoral head-neck junction. The proportional measured alpha-angle resection were 18±11% and 23±11% (axial and radial, respectively). Part of this data had been previously published in Beaulé et al (2017)[6].