PRE- AND POST-OPERATIVE BIOMECHANICS IN FEMOROACETABULAR IMPINGEMENT PATIENTS DURING LEVEL WALKING

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By
Christine Black

Thesis Committee:

Christopher Stickley, Chairperson
Ronald Hetzler
Kaori Tamura

Abstract

Femoroacetabular impingement (FAI) is a hip bony morphology that causes intra-articular damage that may lead to osteoarthritis. Changes in level walking gait, including abnormal reversals, have been seen previously. Three participants with FAI and labral tears were compared to healthy controls pre-operatively, three, and six month post-operatively. Changes were seen within the FAI group and compared to the control group. Increases in survey scores indicated an increase in activity levels. Peak dorsiflexion was increased pre-operatively compared to controls and to three and six months post-operatively. Peak propulsive force and peak ground reaction force were increased at three and six months post-operatively. Sagittal plane hip excursion was also increased at six months post-operatively compared to pre-operatively. Magnitude and duration of abnormal reversals were decreased in one FAI participant but increased in another participant. The prevalence of abnormal reversals remained the same in two participants. The change of the hip angle through the reversal was decreased. These changes may be attributed to an increase in ankle strategy while walking to a near normal level and a decrease in the hip strategy seen pre-operatively. The increase in hip sagittal plane excursion has been seen and may indicate the surgery is effective. In conclusion, walking gait biomechanics are affected by FAI and can be changed with arthroscopic surgery. Different strategies may be used to compensate for pain.

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Introduction

Femoroacetabular impingement (FAI) results from bony deformity of the femur or acetabulum.[1,2] Cam, pincer, and mixed FAI are subtypes that identify the location of the osseous abnormality. Cam FAI occurs when decreased concavity or offset of the femoral head-neck junction[1] leads to abutment between the aspherical head and the acetabular rim during extreme motion.[1,2] Pincer FAI occurs when acetabular over-coverage leads to early contact between the acetabular rim and the femoral neck, as seen in conditions like coxa profunda and acetabular retroversion.[1,2] Mixed FAI features both cam and pincer deformities.

These abnormal contacts lead to changes in motion and progressive joint damage.[1,3] Passive hip flexion, adduction, and internal rotation are reduced secondary to the bony architecture of the joint,[3-7] and intra-articular damage occurs where the bones collide in terminal motion.[1,3] Cam FAI leads to labrum tears and articular cartilage abrasions in the anterosuperior region, while pincer impingement leads to labral degeneration, ossification of the rim, and chondral damage.[2] During the early stages of disease progression, insidious pain is exacerbated by increased activity and advancing intra-articular damage coincides with pain increases[7]. Eventually, activities of daily living (ADLs) such as putting on shoes, getting in and out of a car, prolonged sitting and walking become problematic.[1,3,7]

Symptomatic FAI leads to functional deficits during squatting[8], stair climbing[9] and level walking gait[9-13]. Previous walking gait studies have found abnormal kinematics and kinetics compared with healthy controls.[9,11-13] Hip sagittal plane motion is often a

primary focus of these studies due to the typical patterns of deficits in these patients. Decreased sagittal plane excursions (excursion = peak hip flexion + peak extension) are attributed to both a decreased peak hip extension[11,13] and hip flexion[9]. Abnormal reversals (second order changes in the slope of the sagittal plane graphs[10]) are seen approximately four times more often in symptomatic FAI patients than healthy controls.[9] These reversals may be a precursor to OA or seen as a compensatory pattern when the femoral head is aspherical.[14] Similar to sagittal plane changes, frontal plane hip excursion[11-13] has been attributed to both decreased peak hip abduction[12,13] and adduction angles[11]. Additionally, reduced hip and pelvic excursions[13] have also been reported in the transverse[11] and frontal planes, respectively. No kinematic differences have been reported between FAI patients and controls at the knee, ankle, and pelvis, however, the samples were limited to patients with cam impingement[13] and only included either an open or combined procedure[12]. Kinetically, a mixed sample of uni- and bilateral FAI patients displayed decreased peak external hip flexion and external rotation moments[11], while a sample of unilateral FAI patients reported no differences in kinetics[13].

Post-operative outcomes include increased activity and decreased pain levels[9], but cases of residual stiffness and decreased function have been reported[12]. It is possible that the decreased pain alone leads to improved walking gait kinematics in these samples. Increased sagittal hip excursion, due to increased peak hip flexion, may contribute to returning post-operative FAI patients to equal levels of controls.[9] Pre-operative abnormal reversals have been shown to decrease in both magnitude and prevalence after surgery.[9-11,14] However, no improvements were found post-operatively for peak joint angles, excursions, and peak moments for the hip, knee, ankle, and pelvis.[12]

Current biomechanical studies utilize differing methodologies, which make drawing inferences difficult. Studies have included differing surgical procedures (arthroscopic[9,11], open[12], combined[12]), have included samples of bilateral patients[11], and have limited data analysis to hip and pelvis kinematics[9]. No researchers have explored what is happening at the thorax or the knee and ankle joints during abnormal reversals. Additionally, even though immediate changes in passive range of motion (ROM) have been identified intra-operatively and three months post-operatively[5], no studies have collected post-operative data earlier than the one year following surgery. Further, while some studies have found differences in peak joint angles[9,11-13], moments[7,11,13], and abnormal reversals[9,11], others have not[12]. Therefore, the purpose of this study is to investigate walking kinetics and kinematics pre-operatively and three and six months post-operatively in patients diagnosed with FAI compared to a healthy control population. We hypothesize there will be increases in UCLA and HOS scores at three & six months compared to pre-operatively. Also, there will be a significant decrease in hip sagittal and frontal plane excursion pre-operatively in FAI patients compared to controls, and no significant differences between groups at the three and six months post-operative time periods. Additionally, we hypothesize abnormal reversals will be present pre-operatively in FAI patients but not in controls. The reversals in the FAI group will decrease in prevalence and magnitude post-operatively by three months. There will be no significant differences in any kinematic and kinetic variables at the six months post-operative time-period between FAI patients and controls, or within limbs of FAI patients.

Methodology

Research Design

A longitudinal prospective research design was used to explore the walking of FAI patients compared to controls. The independent variables were limb (involved or uninvolved), group (control or experimental), and time (data collection session). The dependent variables were peak kinetic forces, peak joint angles, joint excursions, and the presence, duration, magnitude, and timing of abnormal reversals.

Participants

Patients diagnosed with FAI and concomitant acetabular labrum tears and matched controls were recruited from the Kapi`olani Medical Center for Women and Children and from the local community, respectively. The inclusion criteria for the FAI group were: unilateral deformity, scheduled for arthroscopic surgery, ability to walk without an aid, and no previous history of hip surgery. Participants with bilateral deformity, avascular necrosis, chrondrolysis, osteoarthritis, pregnancy or nursing were not eligible for inclusion. All participants completed an informed consent and signed consent forms approved by the Western Institutional Review Board prior to study initiation.

Data Collection Sessions

Participants completed all sessions in the University's Human Performance and Gait Laboratory. Experimental participants completed three data collection sessions while controls completed a single session, as it was assumed that gait would not change in otherwise healthy persons[15] (Table 1). The baseline assessment for the FAI group was no more than two weeks prior to surgery and subsequent visits were three and six months

after the surgery. Each data collection session included subjective surveys, collection of anthropometrics, and walking gait analysis.

Table 1. Data Collection Sessions

Group	Baseline	3 months	6 months
FAI Particpants	x	x	x
Control Participants	x		

Surveys

Two surveys assessed the patient's quality of life and activity level. The UCLA Activity Score (UCLA) is ten-item single question survey to evaluate current activity levels.[16] The Hip Outcome Score (HOS) is comprised of two subscales. The activities of daily living (HOS-ADL) subscale is twenty questions and a rating of function; the Sports subscale (HOS-SS) is nine questions and a rating of function during sports-related activities. This survey has been shown to be a reliable tool to assess function after arthroscopic surgery in adults.[17]

Anthropometrics

Height was measured standing using a wall-mounted stadiometer (model 67032, Seca Telescopic Stadiometer, Country Technology, Inc., Gays Mills, WI, USA). Body mass was assessed on a Detecto Certifier scale (model number 442, Webb City, MO, USA). Joint widths were obtained using a GPM anthropometer (DKSH Switzerland Ltd., Zurich, Switzerland). Standing leg length and inter-anterior superior iliac spine distance were recorded using a Gulick tape measure (G&S Fibreflex).

Gait Analysis

A three-dimensional motion capture system (Vicon MX, Vicon, Inc., Centennial, Colorado, USA) and Vicon software (Nexus and Polygon, Vicon, Inc., Centennial, Colorado, USA) were used to capture, reduce, and analyze kinematic data. A 27 reflective

marker set according the lower leg thorax plug in gait model (Vicon) was utilized. Two force plates (Advanced Mechanical Technology Incorporated, Boston, MA) embedded flush with the floor were used to obtain kinetics at 960 Hz and time synchronized with kinematic data collected at 240 Hz. Kinematic and kinetic data were smoothed using a Butterworth filter with a 10 Hz cutoff. The average of three successful trials, one in which the participant's foot landed directly and only on the force plate staying within the borders of the plate while keeping a constant speed and no noticeable change in gait, as patients walked at a self-selected speed down a 10 m runway were used for analysis.

Statistical Analysis

Descriptive statistics including means, standard deviations, and ranges were calculated for demographic information including age, height, and body mass. Data were averaged for each time period, limb, and among trials for variables related to abnormal reversals including magnitude, duration, prevalence and occurrence during stance. Magnitude of abnormal reversals was measured from the maximum peak to the minimum peak; duration was also calculated between these two points and presented as a percentage of stance. The prevalence of reversals was calculated by dividing the number of trials with the presence of abnormal reversals by the total number of trials. Location was presented as the percentage of stance at the mid-point of the abnormal reversals. The change in joint sagittal plane angle was calculated for the hip, knee, and ankle by subtracting the joint angle at the end of the reversals from the joint angle at the start of the reversals. The joint angles at the start and end of the abnormal reversals and the change of the joint angles were compared between the FAI group and controls without reversals using independent t-tests. Peak joint angles, excursions, and kinetic forces were

analyzed by 1x3 repeated measures analyses of variance (ANOVA) within subject designs and three one-way ANOVAs to analyze the group comparisons. Intra-limb symmetry of kinematics and kinetics in the FAI group were assessed via matched pairs t-tests. All statistical analyses were completed using SPSS v22 (SPSS Statistics, IBM Corporation, Armonk New York, USA). Alpha levels were set at $p < 0.05$.

Results

Participant demographics are summarized in Table 2. The FAI group consisted of three participants who underwent arthroscopic surgery for acetabular labral tears. Two had mixed FAI, while one had cam only. The control group consisted of three healthy individuals. There were no significant differences in age (F=0.077, p=0.983), height (F=0.454, p=0.786), mass (F=0.504, p=0.783) and BMI (F=0.408, p=0.836) between FAI and control groups.

Table 2. Participant Characteristics Preoperatively: Mean (Standard Deviation)

	Gender	Age (yrs)	Height (mm)	Mass (kg)	BMI	FAI Type
Patients	1 M, 2 F	34.0 ± 12.5	1676.3 ± 55.5	66.3 ± 14.1	26.1 ± 3.8	2 Mixed, 1 Cam
Controls	1 M, 2 F	30.7 ± 6.5	1729.3 ± 74.5	78.4 ± 15.0	23.4 ± 3.4	N/A

M = Male, F = Female, C = Cam, P = Pincer, yrs = years, mm = milimeters, kg = kilograms

The UCLA activity score and $HOS_{(ADL)}$ and $HOS_{(SS)}$ were collected and averaged. The average UCLA score for controls was 8.67, and the $HOS_{(ADL\ and\ SS)}$ at 100, meaning no difficulty at all, and 100% ratings of ADLs and sports functionality. Pre-operatively, the UCLA score was 5, $HOS_{(ADL)}$ was 68.86 and rating of function was 55% and $HOS_{(ss)}$ and rating of function were 38.89, extreme difficulty, and 21.67%. At three months post-operatively, the UCLA score increased to 6.33while the $HOS_{(ADL)}$ score and rating increased to 77.63, slight difficultly, and 66.67, respectively. The $HOS_{(SS)}$ increased to 50, moderate difficulty, and the rating increased to 43.33. Increases were seen again at

six months post-operatively. The UCLA score increased to 10, while the $HOS_{(ADL)}$ score and rating increased to 89.91, no difficulty, and 83.33, respectively. The $HOS_{(SS)}$ and rating increased to 87.96, no difficulty, and 83.33 (Table 3).

Table 3. UCLA and HOS Survey Results

Group	UCLA	ADL score	ADL rating of function	Sports Score	Sports rating of function
Control	8.67	100.00	100.00	100.00	100.00
FAI Pre-Operative	5.00	68.86	55.00	38.89	21.67
FAI 3 Mo. Post-Operative	6.33	77.63	66.67	50.00	43.33
FAI 6 Mo. Post-Operative	10.00	89.91	83.33	87.96	83.33

Significant kinematic and kinetic differences were found between FAI and control groups during walking. Peak ankle dorsiflexion angle was the only variable to be increased pre-operatively in FAI participants when compared to controls ($F_{1,2}$ = 17.93, P = .001). The foot progression angle at 30% of stance was decreased and timing of ankle internal rotation was earlier pre-operatively compared to controls and remained lower ($F_{1,2}$=9.547, p=0.006, p=0.016, p=0.012, respectively) and earlier ($F_{1,2}$=18.602, p=0.001, p=0.004, p=0.001, respectively) at three and six months post-operatively. Peak knee abduction moment ($F_{1,2}$=6.613, p=0.022) was reduced at three months post-operatively, and hip internal rotation moments ($F_{1,2}$=0.619, p=0.003) were reduced pre-operatively (Table 4.).

Table 4. Significant Differences Between FAI and Control Participants

Variable	Controls	FAI-P	FAI-3	FAI-6	p-value			F ratio
					C v FAI-P	C v FAI-3	C v FAI-6	
Peak DF Angle	13.31 ± 1.33	17 .81 ± 0.38	14.65 ± 0.74	14.23 ± 0.33	**0.001***	0.244	0.520	17.927
Timing of Peak Ankle Internal Rotation	84.33 ± 14.33	0 .70 ± 0.09	17.14 ± 28.25	1.01 ± 0.59	**0.001***	**0.004***	**0.001***	18.602
Foot Progression at 30% Stance	4.61 ± 5.79	-8 .05 ± 2.26	-6.13 ± 0.50	-6.68 ± 1.99	**0.006***	**0.016***	**0.012***	9.547
Peak Knee Abduction Moment	-58.84 ± 14.43	-25 .03 ± 10.32	0.42 ± 33.46	-57.74 ± 6.40	0.215	**0.022***	1.000	6.613
Peak Hip IR Moment	181.22 ± 7.19	97 .09 ± 27.26	132.42 ± 22.72	136.35 ± 12.41	**0.003***	0.056	0.080	0.619

DF = Dorsiflexion, IR = Internal Rotation, FAI-P = preoperative, FAI-3 = 3 months, FAI-6 = 6 Months, C = Control, Mean ± SD, * Indicates significant difference

Significant changes occurred within FAI participant's kinematics and kinetics post-operatively. Peak ankle dorsiflexion angles decreased at both three ($F_{(1,2)}$=36.745, p=0.011) and six months ($F_{(1,2)}$=36.745, p=0.010) compared to pre-operative values, whereas peak plantarflexion velocity ($F_{(1,2)}$=7.457, p=0.040) increased post-operatively. Knee transverse plane position at push-off ($F_{(1,2)}$=9.580, p=0.036) was increased by three months, while timing of knee rotational velocity ($F_{(1,2)}$=0.692, p=0.034) occurred later and mean knee flexion velocity ($F_{(1,2)}$=2.355, p=0.050) increased from three months to six months, returning to similar pre-operative values. Hip excursion from heel strike to peak extension ($F_{(1,2)}$=1.064, p=0.029) was increased at six months post-operatively, and position at push off in the sagittal plane ($F_{(1,2)}$=3.826, p=0.017) increased from three to six months. Peak frontal plane pelvis angle ($F_{(1,2)}$=0.534, p=0.016) decreased from three to six months.

Peak propulsion force ($F_{(1,2)}$=134.588, p=0.009, p=0.003, respectively) and peak ankle internal rotation moment ($F_{(1,2)}$=9.470, p=0.049, p=0.043, respectively) were increased at three and six months postoperatively compared to pre-operatively. Peak ground reaction force (GRF) ($F_{(1,2)}$=2.013, p=0.043) was increased at six months compared to pre-operative values. Peak knee extension moment ($F_{(1,2)}$ =1.652, p=0.018) increased from pre-operative values at three months post-operatively. The timing of max ankle dorsiflexion moment ($F_{(1,2)}$=4.748, p=0.007) was later in stance between three and six months post-operatively (Table 5).

Table 5. Significant Differences within Data Collection Sessions

Variables	FAI-P	FAI-3	FAI-6	p-value P v 3	p-value P v 6	p-value 3 v 6	F-ratio
Ankle							
Peak DF	17.80 ± 0.38	14.65 ± 0.74	14.23 ± 0.33	**0.011**	**0.010**	0.570	36.745
Peak PF Velocity	-372.76 ± 67.07	-387.35 ± 42.64	-432.55 ± 47.16	0.581	**0.040**	0.057	7.457
Knee							
Mean Flexion Velocity	63.06 ± 1.70	67.84 ± 7.07	71.72 ± 6.91	0.437	0.210	**0.050**	2.355
Position at Push-Off - Transverse Plane	6.06 ± 3.50	17.62 ± 6.59	11.54 ± 1.22	**0.036**	0.074	0.236	9.580
Timing of Rotational Velocity	9.81 ± 1.60	8.97 ± 1.15	9.70 ± 1.08	0.448	0.936	**0.034**	0.692
Hip							
Excursion from Heel Strike to Peak Extension	-39.30 ± 5.22	-40.30 ± 4.85	-41.15 ± 4.84	0.551	**0.029**	0.665	1.064
Position at Push-Off- sagittal plane	5.10 ± 7.44	2.59 ± 8.71	7.44 ± 8.68	0.399	0.324	**0.017**	3.826
Pelvis							
Peak Pelvis Angle	2.01 ± 4.32	4.30 ± 1.93	2.49 ± 2.17	0.491	0.887	**0.016**	0.534
Kinetics							
Peak Propulsive Force	1.70 ± 0.28	2.18 ± 0.24	2.32 ± 0.30	**0.009**	**0.003**	0.059	134.588
Peak Ground Reaction Force	10.78 ± 0.98	10.89 ± 0.38	11.25 ± 0.82	0.782	**0.043**	0.319	2.013
Peak Ankle IR Moment	165.05 ± 1.61	188.05 ± 1.29	185.11 ± 2.10	**0.049**	**0.043**	0.725	9.470
Timing of Peak DF Moment	78.50 ± 1.58	79.63 ± 0.76	79.13 ± 0.92	0.145	0.254	**0.039**	9.811
Peak Knee Extension Moment	-285.67 ± 83.35	-402.86 ± 107.89	346.92 ± 158.63	**0.018**	0.498	0.489	1.652
Peak Knee ER Moment	-24.28 ± 5.21	-21.93 ± 8.21	-36.47 ± 9.50	0.583	0.125	**0.007**	4.748

DF = Dorsiflexion, IR = Internal Rotation, FAI-P = preoperative, FAI-3 = 3 months, FAI-6 = 6 Months, Mean ± SD, * indicates significant difference

Intra-limb differences were seen within control and FAI participants. Controls had increased vertical GRF impulse (p=0.044, t=-4.632), hip peak extension velocity (p=0.016, t=-7.912), and later timing of peak extension velocity (p=0.002, t=-20.76) in the right limb. The timing of peak hip adduction moment (p=0.048, t=4.416) was earlier in the right limb. Pre-operatively in the FAI group, no significant differences were found. At three months post-operative, peak ankle eversion (p=0.023, t=-6.476) was decreased in the involved limb. Peak ankle internal rotation angle (p=0.030, t=5.607), ankle position at heel strike in the transverse plane (p=0.023, t=6.531), and mean foot progression angle during stance (p=0.031, t=5.514) were increased in the involved limb. At six months post-operatively, timing of peak ankle inversion (p=0.044, t=-4.629), peak thorax angle (p=0.014, t=-8.244), and GRF impulse (p=0.015, t=-7.947) were later or decreased in the involved limb. Peak knee flexion moment while loading (p=0.016, t=7.84) and peak hip adduction moment (p=0.028, t=5.812) were increased in the involved limb (Table 6).

Table 6. Intra-limb Symmetry

Controls	Left Limb	Right Limb	p-value	t-value
Peak hip extension velocity	-169.5200 ± 57.5731	182.0300 ± 19.3892	0.016	-7.912
Timing of peak hip extension velocity	23.5700 ± 7.3893	98.2800 ± 2.9752	0.002	-20.76
Transverse plane ground reaction force impulse	321.7300 ± 81.2538	327.7000 ± 83.3732	0.044	-4.632
Transverse plane ground reaction force impulse normalized	0.4900 ± 0.0245	0.5000 ± 0.0264	0.015	-7.984
Timing of hip peak adduction moment	26.4500 ± 2.1870	23.6400 ± 3.0087	0.048	4.416
FAI-P	**Involved Limb**	**Uninvolved Limb**	**p-value**	**t-value**
none				
FAI-3	**Involved Limb**	**Uninvolved Limb**	**p-value**	**t-value**
Peak eversion angle	0.0280 ± 3.0900	3.1200 ± 2.5100	0.023	-6.476
Ankle position at heel strike in the transverse plane	1.5800 ± 6.6000	-4.7800 ± 5.2000	0.023	6.531
Peak ankle internal rotation angle	1.9900 ± 6.9000	-4.6200 ± 5.2700	0.03	5.607
Mean foot progression during stance	2.7600 ± 2.5900	1.4000 ± 3.0200	0.031	5.514
FAI-6	**Involved Limb**	**Uninvolved Limb**	**p-value**	**t-value**
Timing of peak ankle inversion	37.7978 ± 30.8915	87.9479 ± 20.8749	0.044	-4.629
Peak thorax angle	4.2704 ± 1.3550	4.7570 ± 1.2588	0.014	-8.244
Ground reaction force impulse	392.6078 ± 108.0514	401.2835 ± 109.2513	0.015	-7.947
Ground reaction force impulse normalized	0.4948 ± 0.0340	0.5060 ± 0.0338	0.01	-9.75
Peak knee flexion moment while loading	602.7413 ± 439.1651	449.6810 ± 436.1925	0.016	7.84
Peak hip adduction moment	1098.2730 ± 300.6102	960.4227 ± 259.9970	0.028	5.812

FAI-P = preoperative, FAI-3 = 3 months, FAI-6 = 6 Months, Mean ± SD

Abnormal hip flexion reversals were found in all three of the FAI participants. Means of the location, duration, and magnitude of the reversals were determined (Table 7). The hip, knee, and ankle angles in the sagittal plane at the timing of abnormal reversals and the corresponding controls were calculated (Appendix K-M). The change in sagittal plane hip angles (p=.001, t=4.921) was significantly different as the FAI group moved into flexion while controls moved further into extension (Table 8).

Table 7. Pre- and Post-Operative Abnormal Reversal

Participant No.	Loc(% stance)	Dur(% stance)	Mag(degrees)	% Trials
	Pre-Operative Reversals			
1	No Reversals			
5	7.7	7.7	2.3	100.0
7	9.9	4.3	0.6	100.0
	3 Months Post-Operative Reversals			
1	No Reversals			
5	8.2	7.3	3.3	100.0
7	12.3	5.3	1.4	100.0
	6 Months Post-Operative Reversals			
1	10.5	1.0	0.0	33.3
5	8.7	6.7	0.9	100.0
7	13.9	7.3	2.6	100.0

Loc - Location, Dur - Duration, Mag – Magnitude

Table 8. Differences in Abnormal Reversals

Variable	Control	FAI	p-value	t-value
Change of hip angle	-2.58 ± 1.70	1.63 ± 1.16	0.001	4.921

Mean ± SD

Discussion

The primary findings in this study were that gait and activity level improvements were seen in FAI participants compared to healthy controls following surgery. Activity levels increased from pre-operative values at both three and six months. At six months,

UCLA scores were similar to controls, but the HOS scores and ratings of function for both ADL and Sports subscales were lower than controls. This indicates some degree of difficulty with ADLs and recreational sporting activities possibly due to the need for continued healing from the surgery. Decreased sagittal plane hip excursion was found pre-operatively compared to six months post-operatively. The increase was related to an increase in both peak flexion and peak extension, as neither was independently significant. Previous studies have reported increased sagittal plane excursion one year post-operatively in FAI patients due to increased peak hip flexion.[9,10]

Hip and ankle strategies are used to transition from stance to swing phase, and a tradeoff is seen between these two strategies[18]. The decrease in peak dorsiflexion and increase in peak plantarflexion velocity suggests an increase in ankle strategy from pre-operatively to six months post-operatively. This is caused by an increase in ankle push-off leading to less force at the hip. Ankle plantarflexion power propels the leg into swing and shifts body mass forward and is known as an ankle strategy[18]. The hip strategy uses the hip flexors to concentrically pull the swing leg forward or the hip extensors of the stance leg contract to posteriorly rotate the pelvis and assist with the forward movement of the contralateral leg into swing[18,19]. Some clinicians believe increasing the ankle pushoff may allow for an avoidance pattern of gait for patients with anterior hip pain[18]. The increase in ankle strategy may be due to an adaption caused by the pain and swelling after surgery and continued on to at least six months post-operatively. Participants did not report any pain while walking at any data collection session. The ankle strategy is thought to be the preferred strategy in young, healthy adults[18] and an increase in the

strategy may mean a return to normal gait. This is evidenced by the lack of difference in dorsiflexion angle in between controls and three and six months post-operatively.

Peak propulsive force was also significantly increased at three months post-operatively. This corresponds with the trend of increased ankle strategy after surgery. Peak propulsive force and peak GRF were significantly increased at 6 months compared to pre-operative values, meaning the change in gait continued. This is seen as the pushoff from the ankle has been increased causing a greater force. The timing of peak dorsiflexion moment was later in stance at six months post-operatively. This could be related to the increased ankle strategy and a decreased dorsiflexion angle at this time period.

Abnormal reversals were seen in all three FAI participants. The duration and magnitude were decreased from pre-operatively to six months post-operatively in one participant. Another participant had increased duration and magnitude. Both of the previously mentioned participants had reversals present in all trials at all data collection sessions. The last participant had only one trial with an abnormal reversal. These results vary from previous literature as a decrease in prevalence, magnitude, and duration has been reported[10]. When compared to controls, there was a difference in the change in hip sagittal plane angle. This was expected as the hip moves into flexion for an abnormal reversal, and the controls moved into extension, decreasing the flexion angle at the same percentage of stance. Compensations at other joints were expected, but none of the changes were significant. With increased samples, changes may be seen at the knee as the difference was approaching significance (p=0.060).

These abnormal reversals may be caused by abnormal femoral head shape or muscle co-activation[14]. The abnormal reversals did not disappear or decrease in prevalence after surgery, indicating the shape of the femoral head either did not cause the reversal or the surgery did not completely correct the shape. The changes in magnitude and duration were different for each participant, indicating the possibility of the reversals being dependent on FAI subtype and extent of intra-articular damage, especially as the abnormal reversals were increased with increasing damage from OA[14]. It is possible there was muscle co-activation that caused the reversal but we are unable to conclude this without muscle EMG to know if both the hip flexors and extensors were activating simultaneously early in stance.

The limited sample size of each group was a limitation in the present study and additional differences may have been seen with greater power via increased sample size. Additionally, differences kinematics and kinetics may have been seen between cam, pincer, and mixed FAI, but these morphologies were included in the same group in the present study. Cam and pincer FAI affect the intra-articular tissue differently, creating varying damage. The area of the damage for pincer can be more posterior than damage caused by cam. This could cause differing compensation patterns to avoid placing forces through the damaged area. Lastly, control subjects did not have imaging or clinical exam for hip pathologies. Previous literature stated at least one predisposing factors of FAI were present in 33% of females and 52% of males in one or both hips[20], while 4.8% of females and 7.3% of males had positive impingement tests in at least one hip[21]. Controls did not have pain in the lower limbs and walking would not reach the terminal ROM, therefore not causing impingement in the asymptomatic controls.

Further studies may be able to expand on the knowledge of biomechanics in FAI patients. More FAI and control participants would increase the power and definitive conclusions may be able to be drawn. Grouping by the FAI subtype may also allow for different findings as the subtypes create slightly different soft tissue damage. Also, including time periods longer than six months would be beneficial to determine the long term outcome of the surgical procedure.

Conclusion

Walking gait biomechanics are affected by FAI and can be changed with arthroscopic surgery. Different ankle and hip strategies may be used to compensate for pain caused by intra-articular damage and change strategies after surgery. Further studies should be completed in order to draw more consistent and definitive conclusions.

Literature Review

Femoroacetabular impingement (FAI) is a bony deformity of the hip that causes intra-articular damage and pain. This may lead to changes in wailing gait kinematics and kinetics. Surgery may be done either with an open, arthroscopic, or combined procedure in order to fix the damage and pain. Because this is a relatively new and misdiagnosed injury, the research involving FAI biomechanics is limited but rapidly growing.

Development, Signs, and Symptoms of FAI

Agricola et al. evaluated the development of cam-type FAI in young, elite soccer players. Boys from ages 12 to 19 years old who played in selection teams of the Feyenoord soccer club in the Netherlands and followed a particular program to train were selected for this study. Of the 141 total, 89 gave consent and had clinical and radiographic evaluations completed. Controls were boys of the same age with both AP and frog-leg lateral radiographs of both hips available but were not diagnosed with a hip disorder by a pediatric orthopedic surgeon or musculoskeletal radiologist. Participants were excluded if sports practice was reported in medical records but not excluded when a cam-type deformity without any other hip disease was diagnosed. There were 92 participants in the control group. Range of motion was measured in flexion, extension, abduction, adduction, internal rotation, and external rotation by a goniometer. The impingement test was considered positive with sharp pain in 90 degrees of flexion with adduction and internal rotation. Significantly more prominences in the head-neck region were scored visually in soccer players than in controls and the prevalence increased with age. A flattening of the head-neck region was significantly more frequent in soccer players. Internal rotation was significantly reduced in hips with a cam-type deformity

determined by an alpha angle of greater than 60 degrees compared to hips without cam-type deformities[22].

Range of Motion

Audenaert et al. investigated the range of motion (ROM) of patients with FAI, participants with radiographic evidence of this bony morphology, and healthy controls. This study consisted of 42 subjects, all of whom were male between the ages of 18 and 35 years. Eighteen cam patients were recruited from patients scheduled for treatment and present with typical signs and confirmed by a radiography and arthro MRI. Twelve healthy controls and asymptomatic cases were recruited from healthy volunteers with a negative history of groin pain, the absence of clinical signs on impingement testing, and bilaterally an alpha angle of less than 50 degrees for healthy controls and greater than 55 degrees for asymptomatic cases. Kinematic measurements were performed using the Fastrak electromagnetic tracking system. External rotation, internal rotation, flexion, and internal rotation in 90 degrees of flexion ROM were evaluated. Each motion was repeated 10 times, the median value was used for analysis. One-way analysis of variance was performed to evaluate the differences between groups. Significant differences were found for the range of internal rotation during impingement testing, flexion, neutral internal, and neutral external femoral rotation between FAI patients, asymptomatic cases, and controls. Post-hoc testing showed no significant difference between asymptomatic cases and controls. Compared to the control group, patients showed a significantly decreased flexion and internal rotation during impingement testing and a decreased neutral internal and external femoral rotation. Compared to asymptomatic cases, patients

were significantly decreased internal rotation during impingement testing and external femoral rotation[6].

Kubiak-Langer et al. assessed the difference in excursion of patents with FAI to controls and location to the impingement zone in hips. Using CT scans, a virtual 3-D model of the hip was created to analyze hip motion patterns. The ROM and location of impingement can be animated for any pattern. The control group was selected from contralateral hips of patients undergoing CT-based, computer-assisted, image guided THA. Thirty-three hips were used for the control group, and 28 hips with anterior FAI were used for comparison. There were more men in the FAI group and had a significantly lower mean age. The FAI group was split into subgroups by specific type: cam, pincer, and combined. The effect of surgical treatment on internal rotation was simulated for acetabular rim trimming and femoral offset creation. Hips with FAI had decreased flexion, internal rotation in 90 degrees flexion, and abduction when compared to the control group. The zones of impingement were localized to the anterosuperior quadrant and did not differ when comparing the control to the FAI group. The virtual resection of osseous prominences led to an increase of flexion, internal rotation in 90 degrees flexion, and abduction.[23]

Kelly et al investigated the relationship between changes in hip internal rotation and the correction of the alpha angle by arthroscopic cam decompression. Participants were included if they were under 40 years old, diagnosis of symptomatic labral tear, FAI with cam type or combined cam and pincer lesions, and symptoms consistent with FAI but unrelieved by conservative treatment. Participants were excluded for osteoarthritis. Participants underwent hip range of motion testing at initial consultation, preoperatively

under anesthesia, postoperatively under anesthesia, six weeks postoperatively, and 3 months postoperatively. Hip flexion, abduction, and internal and external rotation at 90 degree of flexion were recorded each time using a manual goniometer. Standard radiographs, magnetic resonance scans, and computed tomography were taken in order to evaluate the alpha angle, neck-shaft angle, center-edge angle, femoral neck version, and acetabulum version at three difference locations. Hip arthroscopy was used for labral debridement or refixation and identification and decompression of the pincer and cam lesions. Fifty-five participants were included, one with bilateral symptoms. The average age was just under 25 years. After decompression, the alpha angle was significantly decreased when measured on both modified lateral radiographs and on AP radiographs. Internal rotation increased significantly from preoperatively to immediately after decompression and at three months postoperatively. The decrease in alpha angle was correlated with the magnitude of the increase in internal rotation. Hip flexion was significantly increased from preoperatively to three months postoperatively.[5]

Clinical Presentation of FAI

Clohisy et al. determined the clinical history, functional status, activity status, and physical examination findings that characterize FAI in 51 participants. The diagnosis of FAI was made on clinical and radiographic evidence by the senior authors. This included claims of hip pain, hip joint irritability during special tests, restricted hip range of motion, and radiographic evidence. Structural abnormalities consistent with FAI included acetabular retroversion, coxa profunda, coxa protrusion, aspherical femoral head, or femoral head-neck offset. The average age of the 51 participants was 35 ranging from 15 to 61 years old, and 29 participants were male. A comprehensive questionnaire was use

to obtain medical history and symptoms including onset of pain, location, character, severity, duration, and aggravating and alleviating factors. Participants also reported the time and events prior to diagnosis of FAI such as age of onset of symptoms, previous diagnoses, and number of previous healthcare providers seen. Standard measures of hip function, overall health, and activity were obtained using modified Harris hip score, SF-12, and UCLA scores. The same orthopedic surgeon evaluated the participants to determine bilateral hip range of motion and special tests including Patrick's/FABER, hip log roll, resisted straight leg raise, anterior impingement and posterior impingement signs. Conservative measures such as nonsteriodal anti-inflammatory medications, physical therapy, and activity modifications had failed, leading to a recommendation of surgery to all the patients[7].

Ganz et al. described the clinical presentation, radiographic findings, mechanism, types of FAI, and surgical procedures. It is believed that the abnormal contact in FAI leads to lesion of the labrum and cartilage in young, active adults. These lesions continue to progress and result in degenerative disease, osteoarthritis, of the joint if the underlying cause of impingement is addressed. FAI presents in active young adults with a slow onset of groin pain. It is intermittent in the beginning stages and is exacerbated by athletic activities and prolonged walking. The pain may be present with prolonged sitting. Examination of the hip reveals limited internal rotation and adduction in flexion. The impingement test is usually positive because of shearing forces at the labrum and creates pain at a chondral lesion, labral lesion, or both. An AP and a lateral radiograph are routinely taken. The presence of a bony prominence on the anterolateral head and neck junction, reduced offset of the femoral head and neck junction, and changes to the

acetabular rim may be better seen on lateral radiographs. Morphologic changes such as retroversion, anterior over coverage, coxa profunda, protrusion acetabula, coxa vara, extreme coxa valga, or subtle dysplasia may become apparent on plain radiographs. Radial sequence MRI arthrograms are needed to observe the labrum and acetabular cartilage. The first type, cam impingement, is caused by jamming of an abnormal femoral head with increasing radius into the acetabulum during forceful flexion. This results in shear forces causing abrasion of the acetabular cartilage and/or avulsion from the labrum in the anterosuperior rim. The second type, pincer impingement, is the result of general or local anterior over coverage. The labrum is the first structure to fail because of continued impact of the abutment on the degenerating structure. Chronic leverage of the head in the acetabulum can result in chondral injury on the posteroinferior acetabulum. Surgical dislocation may be used to correct the bony abnormalities. This allows for a full view of the femoral head and acetabulum for inspection. This allows for removal of the nonspherical portion of the head and reducing the anterior over coverage of the acetabulum while being able to repair or excise the damaged labrum and chondral damage.[1]

Yen et al. defined the clinical and radiologic diagnosis of FAI. Proper diagnosis usually occurs after several physician visits and many of the specialized examination tests can be sensitive to hip disorders but not specific. A thorough patient history is needed to evaluate the injury. The patient may describe their pain using a C-sign, cupping the hip anterior to posterior. Intra-articular hip pathologies can refer pain in to the anterior groin, buttocks, greater trochanter, thigh, or medial knee. The functional status is important to understand the presence of symptoms under a load or because of rotation. Pain can be

found with activities of daily living or increases of pain with higher intensity activities, twisting maneuvers, or positions in excessive flexion. Symptoms such as locking, popping, or catching may be indicative of both intra-articular and extra-articular pathology. Physical examination is used to confirm a diagnosis and rule out missing potential diagnoses. The patient may present with a slightly flexed hip and ipsilateral knee. Pain with log rolling of the leg in an extended position can indicate hip pathology including damage of the femoral head, acetabulum, or labrum. The impingement test is performed by combining flexion, internal rotation, and adduction. A scour test can test whether the hip pain is intra-articular by the presence of a catch, click, or bumping which suggests FAI. This test requires rotating the hip in the arc of motion with both the hip and flexed. The Patrick test can also elicit symptoms by placing the hip in flexion, abduction, and external rotation and forcefully reaching the end range. Anterior pain may suggest FAI or psoas tendonitis. The McCarthy test is performed by bringing both hips into full flexion, then extending the affected hip in both internal and external rotation. The test is considered positive if pain is reproduced and indicates an acetabular labral tear. Cam impingement can be seen on the AP pelvis or lateral radiographs. Pincer impingement may be seen on the AP radiograph. Scans such as CTs, MRIs, and MRAs may assist in creating a three dimensional model of the joint and assessing the labral and cartilage damage in the hip.[2]

Asymptomatic FAI

Kang et al. investigated the prevalence bony abnormalities predisposing to FAI in asymptomatic individuals. These abnormalities included acetabular retroversion, acetabular overcoverage, coxa profunda, decreased femoral head-neck offset, and

asphericity of the femoral head. This study included 50 people from the age of 15 to 40 whom underwent an abdominal CT scan to diagnose unspecific abdominal pain. Participants had no previous history of hip-related problems.

Laborie et al.

Surgical Techniques

Byrd et al. described the need and the techniques used for arthroscopic correction of FAI and intra-articular damage. Arthroscopy may allow for slowing the progression of osteoarthritis and for the return to activity. Indication of surgery included imaging evidence of intra-articular pathology and unresponsive to conservative treatment. The presence of a crossover sign on the radiographs suggested pincer impingement and was treated if it caused difficulty with establishing an anterior portal, created labral damage, or revealed overhanging lip of bone. Cam pathology was identified as a nonspherical head. Pincer impingement was treated using a standard supine three-portal technique. Debridement of the damage labral portion revealed overhanging lip of the acetabulum and was recontoured with a spherical burr. Proximally, the bone is resected to the anterior column of the acetabulum. Anteromedially and laterally, the bone was resected to the margins of healthy labrum. Articular damage, if present, was treated with chondroplasty or microfracture. Cam impingement treatment focused on the articular damage. This was treated with chondroplasty and microfracture depending on the severity. Labral pathology was debrided to create a stable edge. In order to reach the cam deformity, a capsulotomy was needed and released a portion of the head of the rectus femoris. The hip was then flexed to 35 degrees in order to visualize the demarcation of abnormal fibrocartilage that covers the lesion. A femoroplasty was then completed to

remove the cam lesion. This required switching of portals to ensure a complete dissection and restoring spherical anatomy. Rehabilitation after surgery started within two days of the procedure and depended on the pathology and procedure. There was an emphasis on optimizing ROM with early implementation of closed-chain joint stabilization and core strengthening exercises.[24]

Outcome Studies

Naal et al. explored the outcomes of surgical hip dislocation in professional athletes. Twenty-two professional hockey, soccer, table tennis, and floorball players (30 hips) were identified because of undergoing a hip dislocation surgery due to FAI and had no sign of osteoarthritis. Mean age at the time of surgery was 19.7, and symptoms were present for a mean of 8.2 months before surgery. Diagnosis was based on history, reduced ROM, positive impingement test, radiographs, and MRI. Surgery was performed in a lateral decubitus position and a Henry approach was used. This uses the interval between the gluteus medius and maximus. A Z-shaped stepped trochanteric flip osteotomy was used instead of flat osteotomy to allow complete dislocation and full visualization of the hip joint. Acetabular and labral lesions were addressed first followed by chondral resection or microfracture as necessary. Osteochondroplasty was performed to optimize the head-neck junction. Rehabilitation was standardized to the injuries seen. Typically, patients returned to competition after four to six months. All patients were sent a questionnaire at a mean of 45.1 months. The questions asked about type of sport, sport level, hip pain during sport, overall satisfaction, the SF-12, the HOS, UCLA activity scale, and their own Hip Sports Activity Scale (HSAS). At the time of the surgery, 21 of the 22 patients still competed professionally, and 19 of the 21 patients maintained their

presymptomatic level. Thirteen patients indicated the surgery improved their ability, six indicated no change, and three experienced deterioration. Mean pain during sports was rated at 1.8 out of 5. Mean activity levels were 9.8 (UCLA) and 7.6 (HSAS) while the HOS ADL subscale was 94.5 and Sport subscale was 89.1. Patients not satisfied with their ability had significantly lower scores for HOS and SF-12. There is growing evidence that treating the underlying pathomorphology to restore normal hip function.[25]

Nho et al. reviewed the clinical and radiographic outcome after arthroscopic treatment of FAI in high-level athletes at different levels of competition. Patients failed nonsurgical treatment and participated in varsity high school, college, or professional sports. Postoperatively, patients underwent a standardized rehabilitation protocol which included immobilization, active and active ROM, and strength and conditioning. The Modified Harris Hip Score (MHHS) and Hip Outcome Score (HOS) were completed by the patients at baseline, six months, one year, and two years after surgery. Time to return to play, strength, and ROM were also measured. The mean MHHS and HOS scores were significantly improved along with the range of motion measured for hip flexion and internal rotation. Seventy-nine percent of the thirty-three patients were able to return to play at an average of 9.4 months. Of these, 92.3 percent were able to return to the same level of competition. At the two year follow up, 73 percent were still competing. Alpha angle was significantly improved.[26]

Bizzini et al. examined the functional and sport-related outcome two years after open surgical decompression of cam FAI in professional hockey players. This case study included five young hockey players of a Swiss professional team diagnosed with cam FAI. All athletes underwent a surgical open hip dislocation, one bilaterally. The athletes

followed the same rehabilitation guidelines and were supervised by the same physical therapist. Range of motion was measured with a goniometer. The sport physical therapist recorded the exact time to regain hip ROM and core and hip muscle strength, and return to unrestricted team training and to competition. Return to pre-operative ROM was achieved at a mean of 10.3 weeks and to pre-operative core/hip strength by a mean of 7.8 months. Athletes were able to return without symptoms to practice at a mean of 6.7 months and to competitive games at 9.6 months. Of the five athletes, three were selected again for the Swiss national teams while the other two were pain- and symptom-free but unable to reach their pre-operative level of performance.[27]

Philippon et al. investigated the outcomes of hip arthroscopy at two to five years after in pediatric and adolescent patients. Each patient was evaluated using a thorough physical examination focusing on positive FABER's and impingement tests and using radiographs. Patients were competitive at their age level. Subjects were deemed surgical after failure of nonoperative treatment for six months. All surgeries were completed by the senior author using the same technique. Subjective data such as a modified Harris Hip Score (mHHS), Hip Outcome Score (HOS) sports subscale, and patient satisfaction with the outcome, were collected from each patient preoperatively, during subsequent office visits, and yearly after surgery. All patients had a positive impingement test, FABER's test, or an alpha angle greater than 60 degrees. Eight hips needed a second-look diagnostic hip arthroscopy because of persistent pain after surgery. During the second-look, all hips presented with capsulolabral adhesions and lysis of the adhesions was performed. Follow-up was obtained at a mean of 3.5 years after the procedure for the patients who did not require revision. The mean mHHS and mean HOS were

significantly improved from the pre-operative scores. The median rating for patient satisfaction with the outcome was ten.[28]

Surveys

Zahiri et al. investigated the use of surveys to assess the activity of patients with joint replacements. The total number of patients was 100 who completed the surveys and recorded use of the pedometer. The ten point University of California Los Angeles (UCLA) was used, then a visual analog scale (VAS) comparing the activity levels to other joint replacement patients, and patients rated his or her activity levels relative to other people were completed. Linear regression analysis was used to determine the correlations between the methods. Both the UCLA activity rating and the VAS rating by the investigator had a strong correlation with the average steps per day. They were also highly correlated with each other. Although there was a high correlation, the amount of steps for a score on the UCLA activity rating was variable by the age of the patient. The patient rating was not correlated with the recorded steps or age. The patients tended to perceive themselves to be more active than they are.[16]

Martin et al. investigated the reliability and responsiveness of the Hip Outcome Score (HOS). The inclusion criteria for the patients were to have undergone evaluation and hip arthroscopy by the senior author. All subject completed preoperative and six month postoperative questionnaires that included HOS. Subjects were divided into two groups depending on the postoperative responses of whether the condition changed or remained unchanged. There were 126 subjects with a mean age of 41 with 53 percent being female. Subjects underwent hip arthroscopy for a variety of reasons including FAI. The intraclass correlation coefficient values were 0.98 and .92 for the ADL and sports

subscales meaning the questionnaire was reliable. The group-by-time interaction was significant for both subscales. This means the questionnaire is responsive. The HOS is reliable and responsive when describing outcomes of the hip arthroscopy.[17]

Computer-Assisted Model Biomechanics

Bedi et al. used computer-assisted 3D modeling to determine objective differences in range of motion before and after arthroscopic surgical treatment of symptomatic FAI. Ten participants with the absence of significant chondral degeneration and previous surgery were included in this study. Preoperative 3D CT analysis revealed evidence of combined pathological abnormalities in all cases. All participants underwent high-resolution CT scans of the involved hip and lower extremity before and within 3 months after arthroscopic surgery that was performed by the same surgeon. These images were used to create a patient-specific 3D hip joint model. Information was imported into MSC.visual Nastran 4D for ROM simulation. The pelvis was fixed in place which allowed for the femur to freely translate in all directions. For preoperative and postoperative simulation, the femur was flexed to 90 degrees and the initial amount of external or internal rotation was measured. The femur was then internally rotated until contact between the neck and the acetabulum was obtained. Clinically, ROM was assessed by the senior author preoperatively and 3 months postoperatively with care to stabilize the pelvis to record measurements using a goniometer. Internal rotation was assessed at 90 degrees of hip flexion. The mean postoperative alpha angle was significantly reduced from preoperatively. The location of the impingement was not predictable based on alpha angle alone and the location of the initial contact was not at the region of maximal loss of offset at the head-neck junction. Mean hip flexion and

internal rotation were significantly increased when comparing the postoperative simulation to the preoperative simulation. The location of the initial contact did not change in the simulation postoperatively. There was an excellent correlation between the clinical measurements and the predicted ROM with no significant difference noted between the preoperative and postoperative ROM.[4]

FAI Biomechanics

Kennedy et al. compared participants with unilateral FAI to healthy matched controls. Seventeen, ten males, had positive impingement tests, visible cam morphology on an anteroposterior radiograph, and had an alpha angle greater than 50.5 degrees. The fourteen matched control participants had no history of serious lower limb injury or surgery and had spherical femoral heads as assessed by an anteroposterior radiograph. Participants were excluded if hip OA was visible or if substantial hip joint space narrowing was visible. Three-dimensional kinematic data were collected using seven VICON MX-13 cameras at 200 Hz with retro-reflective markers placed according to the Helen-Hayes marker set. An AMTI force place captured the kinetic data at 1000 Hz. Participants filled out a WOMAC questionnaire then proceeded to put on a skin-tight suit and performed a stretching warm-up routine. After, the participants completed a sit and reach teat, had markers placed appropriately, and had anthropometric measurements assessed. A static trial was completed in order for segment length calculations to be completed. Participants were asked to walk at a natural speed and completed ten trials, five with their left foot and five with their right foot landing on the force plate. FAI participants had significantly lower peak hip abduction angle, significantly less frontal hip range of motion and lower sagittal hip range of motion than the matched control. The

largest difference in sagittal hip range of motion occurred in hip extension at the end of stance phase[13].

Brisson et al. used 3D kinematics and kinetics of patients before and after surgery compared to healthy controls to examine the outcome of the surgery. Ten patients with unilateral cam impingement returned for post-surgery testing and thirteen healthy, age and weight matched controls participated. All patients underwent either open or combined procedure by the same surgeon. Five trials were taken for each leg while walking barefoot. Patients returned at an average of 21.1 months after surgery for a follow-up data collection. They found reduced hip frontal range of motion compared to the control group. The postoperative group had reduced hip sagittal range of motion compared to the control group. No significant differences were found in knee, ankle, and pelvic kinematics between groups. The postoperative group when compared to the control group produced smaller peak hip abduction, hip internal rotation, knee flexion moments and greater knee flexion moments, and generated less peak hip power[12].

Rylander et al. also looked at the walking biomechanics of FAI participants before and a year after surgery. There were 11 participants who underwent corrective surgery for a variety of cam and pincer FAI mixtures. Nine trials were recorded for each leg for each participant at one month before surgery and one year after. Three walking trials were collected at each self-selected slow, normal, and fast walking speeds. There was a significant increase postoperatively compared to preoperatively in sagittal plane hip range of motion which occurred at maximum flexion and no change of maximum extension. The pattern of hip motion was also found to return more normal characteristics postoperatively. Abnormal reversals were seen in five of the eleven

participants before surgery, but in two of eleven participants one year after surgery. Preoperatively, abnormal reversals were found in 26.6% of trials with an average magnitude of 1.52 degrees, an average duration of 14% of stance, and occurred on average at 56% of the stance phase from heel strike. Postoperatively, abnormal reversals in three participants disappeared. The prevalence and magnitude in one participant was reduced from 43% of trials to 5% and 1.4 degrees to 0.31 degrees. The other participant with abnormal reversals before surgery had an increase in prevalence from 41% of trials to 62% of trials but decreased in magnitude from 0.39 degrees to 0.15 degrees. Location and duration remained unchanged in the two participants with abnormal reversals after surgery. There were no significant differences in hip sagittal plane moments, walking speed, knee sagittal plane range of motion, hip frontal plane range of motion, abduction or adduction angles or moments[10].

Hunt et al. investigated the biomechanical changes in walking gait of symptomatic FAI participants compared to a pain-free control group. Participants were recruited from a tertiary orthopedic surgery clinic by the same orthopedic surgeon. Participants reported having anterior groin pain, exhibited positive impingement signs with a physical examination, and had definitive signs on radiographs and MRIs. Participants were excluded if there were signs of hip osteoarthritis, previous hip surgery, or pain patterns inconsistent with FAI. Control participants were recruited from the University of British Columbia community and therefore a sample of convenience. Participants reported no lower extremity pain or dysfunction, no previous hip joint surgery, and did not exhibit positive signs during hip impingement testing. The groups were similar in age and gender, but the FAI group was significantly taller and heavier.

Data were collected in a single session in which 22 passive reflective markers were placed on the skin over anatomical landmarks using a modified Helen Hayes marker set. Kinematic data were collected using an eight camera system at 120 Hz, while kinetic data were collected from two floor-mounted force platforms in the middle of a 10 meter walkway sampling at 1200 Hz. Five trials with clean platform strikes were obtained for the limb of interest. Trials were conducted barefoot and at the participants' self-selected speed. Participants with FAI walked significantly slower and had smaller cadences than the control group. FAI participants displayed less peak extension, adduction, and internal rotation during stance. One participant exhibited an abnormal reversal in sagittal plane hip kinematics. The reversal occurred at 10 percent of the gait cycle and had a magnitude of two degrees. The FAI group had a decreased peak flexion moment and external rotation moment compared to the control group[11].

Lamontagne et al. compared the kinematics during maximal squatting of patients pre- and post-operatively. Eleven pre-operative patients were compared to fifteen controls and ten patients were compared pre-operatively to post-operatively. Participants were between eighteen and fifty years old with a positive impingement test and a visible cam deformity on radiographs. All patients had an alpha angle of greater than fifty degrees indicating cam FAI. Patients were excluded if there was any sign of OA, contralateral hip pain, and evidence of not a purely cam-type FAI. Three-dimensional lower extremity and pelvis kinematics were collected using nine Vicon MX-13 cameras reading forty five retroreflective markers placed on anatomical landmarks according to a modified Helen Hayes marker set. A height-adjustable bench was used to measure the maximal depth indicator at a third of the tibial plateau height. Each participant

completed five trials to the height of the bench or the lowest attainable depth. Feet were should-width apart and ten centimeters in front of the bench with their arms extended anteriorly. Participants squatted at a self-selected pace until their buttocks slightly touched the bench or to the lowest attainable depth and then ascended back to standing position. There was no significant difference between the pre-operative and post-operative measurements with respect to kinematics of the affected hip at maximal squat depth, pelvic angular displacements at maximal squat depth, or overall pelvic motion. Patients after surgery were able to squat to a greater maximal depth than preoperative values. Postoperative knee flexion and ankle dorsiflexion angles of the affected limb at maximal squat depth were greater than preoperative values. The summation of the joint angles was significantly larger postoperatively compared to preoperative values.[29]

Rylander et al. completed another study to compare walking and stair climbing to healthy controls and before and after surgery. Seventeen FAI patients were recruited from the same surgeon with no history of lower limb injury. A group of seventeen healthy volunteers were matches for age, gender, and BMI. Eleven of the seventeen participants' kinematic data were previously published. All patients had a positive impingement and labral stress tests on the affected side and were free from other lower extremity, spine, and back injuries. Hip and pelvis kinematics were obtained using a nine camera system and calculated using algorithms. Kinetic data were obtained using a force plate. Participants completed an eleven point visual analog pain scale and a Tenger Activity scale survey. Each participant completed three trials per side at a self-selected walking speed and three stair climbing trials per side using two 20 cm stairs without rails and taking one step on flat ground before ascending. All surgeries were performed by the

same surgeon, completing arthroscopic acetabuloplasty and/or cheilectomy. Of the 17 FAI participants, 16 reported a decrease in pain post-operatively and activity level was significantly increases post-operatively. Hip sagittal plane ROM was reduced in the pre-operative FAI limb compared to the controls with most of the reduction in hip flexion. Transverse and frontal plane ROMs were significantly reduced on the pre-operative limb as compared to controls, primarily due to a loss of internal femoral rotation and loss of abduction. The presence of reversals was about four times greater in the FAI group pre-operatively as compared to the controls, but this finding was not significant. In stair climbing, the pre-operative FAI limb had a significant decrease in hip sagittal plane ROM compared to controls stemming from a reduction in extension. A reduction of maximum hip internal rotation was also observed. FAI patients also had a significant increase in transverse plane pelvic ROM and in maximum pelvis anterior tilt as compared to controls. Hip sagittal plane ROM was significantly increased post-operatively and was no longer significantly different from controls. This occurred primarily in flexion. Maximum hip internal rotation was increased to no longer significantly different than controls. The presence of reversals was decreased post-operatively. Hip frontal ROM remained reduced but the loss of abduction was no longer significant. Stair climbing kinematic data were not restored post-operatively. Hip sagittal plane ROM remained significantly reduced in the FAI group as compared to controls. Maximum hip internal remained significantly decreased compared to controls. No differences were found when FAI was divided into subtypes.[9]

OA and Abnormal Reversals

Foucher et al. explored the relationship of hip sagittal plane abnormal reversals, or motion discontinuity (MD), and osteoarthritis. One hundred fifty participants with symptomatic unilateral hip OA with no other lower extremity symptoms and radiographic record of severity of OA determined by Kellgren-Lawrence (KL) grade were recruited for this study. The control group was participants with no hip pain determined by a score of 100 on the Harris Hip Score or less than 10 mm of pain on the WOMAC scale. Passive reflective markers were placed on appropriate lower extremity landmarks and were recorded and analyzed by an optoelectronic camera system. A multicomponent force plate was used to measure ground reaction force and location and inverse dynamics were used to calculate external moments. All participants completed eight trials for each leg at a self-selected normal walking speed. Information for the OA participants used only the involved leg; a leg used for controls was randomly selected. MD was seen in at least one trial in 53% of OA participants and 7.5% of controls. Most OA participants had MD in all of the trials while control participants were more likely to show MD in fewer than half of the trials. Both groups started the MD at 44% or 45% but in OA participants, the duration was shorter at 27% of stance phase compared to 42% for controls. The magnitude was smaller in the control group at 0.8 degrees while the OA group had an average of 1.3 degrees. Logistic regression showed MD was associated with OA and severity of OA. Participants with MD were almost 14 times more likely to have OA than those without MD. KL grade had an odds ratio of 2.19 whish indicated an association between MD and severity of OA. OA participants with MD walked slower than those without. When accounting for the speed difference, MD was associated with

significantly reduced sagittal plane range of motion and peak external and internal rotation moments[14].

Hurwitz et al. investigated gait compensations of patients with OA and compared the results to passive hip motion and pain. The gait of 19 subjects, 12 men and seven women, with the average age of 60 with unilateral osteoarthritis of the hip was evaluated. The subjects underwent a primary total hip replacement following the gait analysis. Nineteen normal subjects with similar age, gender, weight, and height distributions were also tested. Pain and limitations were assessed using the Harris hip analysis, and the Thomas test was used to measure flexion contracture. Joint motion, moments and intersegmental forces were calculated from data collected with an optoelectronic system and a multicomponent force plate. Subjects walked at self-selected speeds of slow, normal, and fast. Inverse dynamics were used to calculate the external moments and intersegmental forces. Significant changes were seen. Hip sagittal plane motion was decreased compared to controls and did not follow the same smooth pattern. Abnormal reversals were present in 74 percent of OA patients with an average duration of 15 percent of stance and a magnitude of two degrees. This reversal occurred in all patients with a flexion contracture of at least 10 degrees, and these patients had a greater loss of active range of motion and greater passive flexion contracture. The OA patients also had a decreased extension moment which was correlated with an increased level of pain.[30]

Gait Analysis

Lewis et al. described the different mechanisms in which to propel the swing leg forward into the next stride. Applying an impulsive push along by the trailing limb allows for redirection of the center of mass forward and upward. Another method is

using a torsional spring. Torque generated by the spring pulls the swing limb forward. There is a direct tradeoff between the impulsive push from the trailing limb and the rotational torque between limbs. Ankle strategy refers to gait powered by ankle plantarflexion or pushoff, which propels the leg into swing and accelerates body mass forward. Hip strategy used the hip flexor muscles of the swing leg to pull the leg forward and the hip extensor muscles in the stance leg contract to posteriorly rotate the pelvis and assist the progression of the contralateral swing leg. Ten healthy subjects, three males, walked at 1.25 m/s split belt treadmill with the ability to measure force in all three planes and reflective markers to record kinematics using a motion capture system. Subjects walked under three conditions: natural pushoff, increased pushoff, and decreased pushoff. Subjects practiced walking under each condition for at least a minute prior to collection. Data were collected for 90 seconds of walking in each condition. This study found that changes in ankle pushoff are inversely related to changes in the internal net hip moments.[18]

Appendix A. UCLA Activity Score

UCLA Activity Score *Please choose the number which best describes your activity level in the last few weeks

10- I regularly participate in impact activities such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking

9- I sometimes participate in impact activities such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking

8- I regularly participate in active activities such as fast walking, golf, or bowling

7- I sometime participate in active activities such as fast walking, golf, or bowling

6- I regularly participate in moderate activities such as moderate walking or heavy house work

5- I sometime participate in moderate activities such as moderate walking or heavy house work

4- I regularly participate in mild activities such as slow walking or limited house work

3- I sometimes participate in mild activities such as slow walking or limited house work

2- I am mostly inactive and restricted to minimal activities of daily living

1- I am wholly inactive and dependent on others

Appendix B. HOS: ADL Subscales

Hip Outcome Score						
Please answer every question with one response that most closely describes your condition within the past week.						
If the activity in question is limited by something other than your hip, mark not applicable (N/A).						
ADL Subscale						
	No Difficulty at All	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to Do	N/A
Standing for 15 min						
Getting into and out of an average car						
Putting on socks and shoes						
Walking up steep hills						
Walking down steep hills						
Going up 1 flight of stairs						
Going down 1 flight of stairs						
Stepping up and down curbs						
Deep squatting						
Getting into and out of a bathtub						
Sitting for 15 min						
Walking initially						
Walking for approximately 10 min						
Walking for 15 min or more						
Because of your hip, how much difficulty do you have with the following:						
Twisting/pivoting on involved leg						
Rolling over in bed						
Light to moderate work (standing. walking)						
Heavy work (pushing/pulling. climbing. carrying)						
Recreational activities						
How would you rate your current level of function during your usual ADL from 0 to 100, with 100 being your level of function before your hip problem and 0 being the inability to perform any of your usual daily activities?						
________________________%						

Appendix C. HOS: Sports Subscale

Sports Subscale						
Because of your hip, how much difficulty do you have with the following:	No Difficulty at All	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to Do	N/A
Running 1 mile						
Jumping						
Swinging objects like a golf club						
Landing						
Starting and stopping quickly						
Cutting/lateral movements						
Low-impact activities like fast walking						
Ability to perform activity with your normal technique						
Ability to participate in your desired sport as long as you would like						

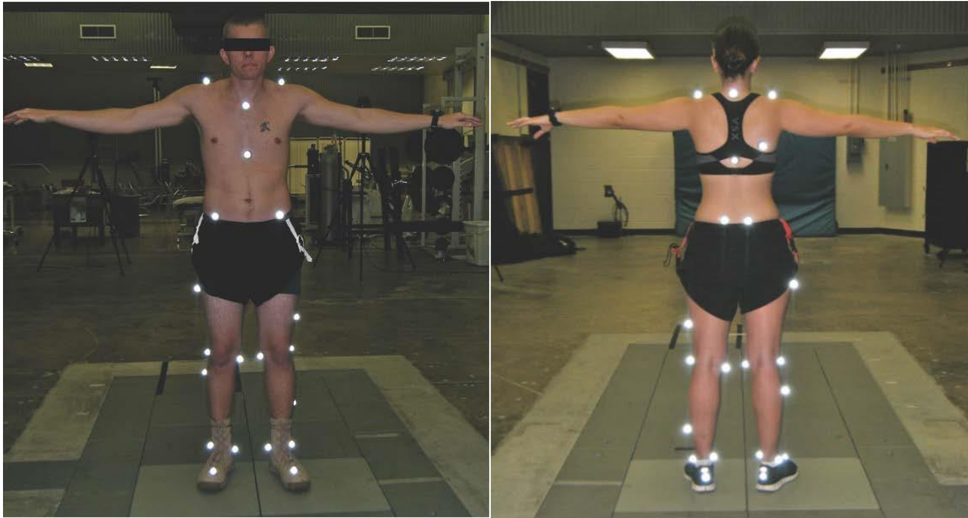
How would you rate your current level of function during your sports-related activities from 0 to 100. with 100 being your level of function before your hip problem and 0 being the inability to perform any of your usual daily activities?

_______________________%

How would you rate your current level of function?

□ Normal □ Nearly Normal □ Abnormal □ Severely Abnormal

Appendix D. Marker Set and Placement



Appendix E. Anthropometric Data Collection Sheet

Anthropometric Data

Subject ID#: ________________ Date__________

Age_________________ Gender: F□ M□

Data Collection Period 0 1 2 3 4 5

Patient's Operated leg: L □ R□ Dominant Leg: L□ R□

Date of Surgery__________________

Vicon/Nexus Measurements

Weight (kg)	
Height (mm)	
Age (yrs)	
Left leg length (mm)	
Left knee width (mm)	
Left ankle width (mm)	
Right leg length (mm)	
Right knee width (mm)	
Right ankle width (mm)	
Inter ASIS (mm)	

Appendix F. Walking Trial Data Collection Sheet

Data Collection Form

Subject ID#: _______________

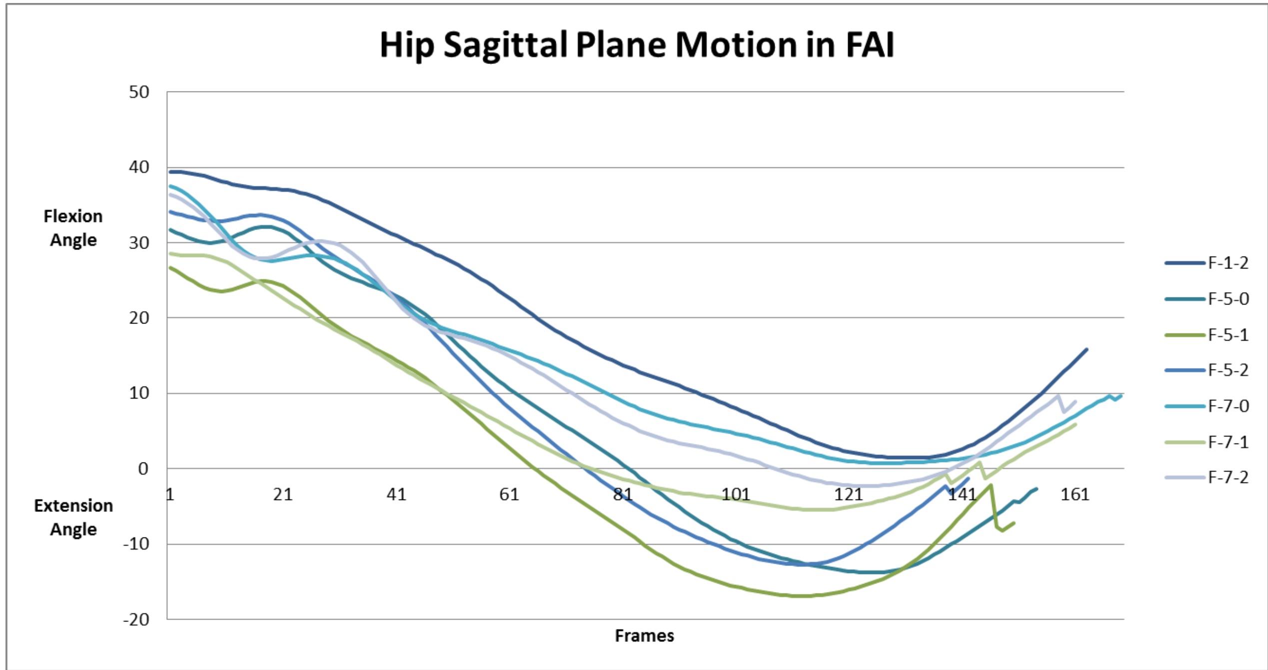
Data Collection Period 0 1 2 3 4 5

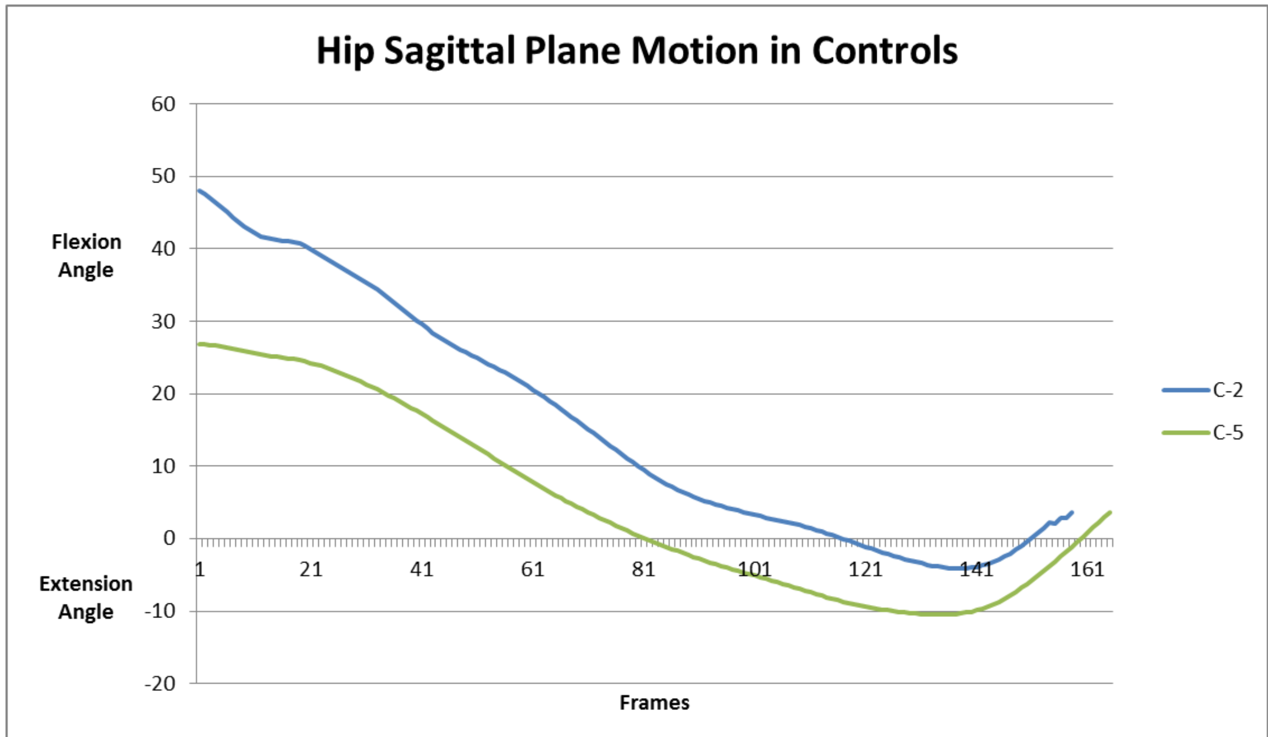
Patient's Operated leg: L□ R□ Dominant leg: L□ R□

Total Trials: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

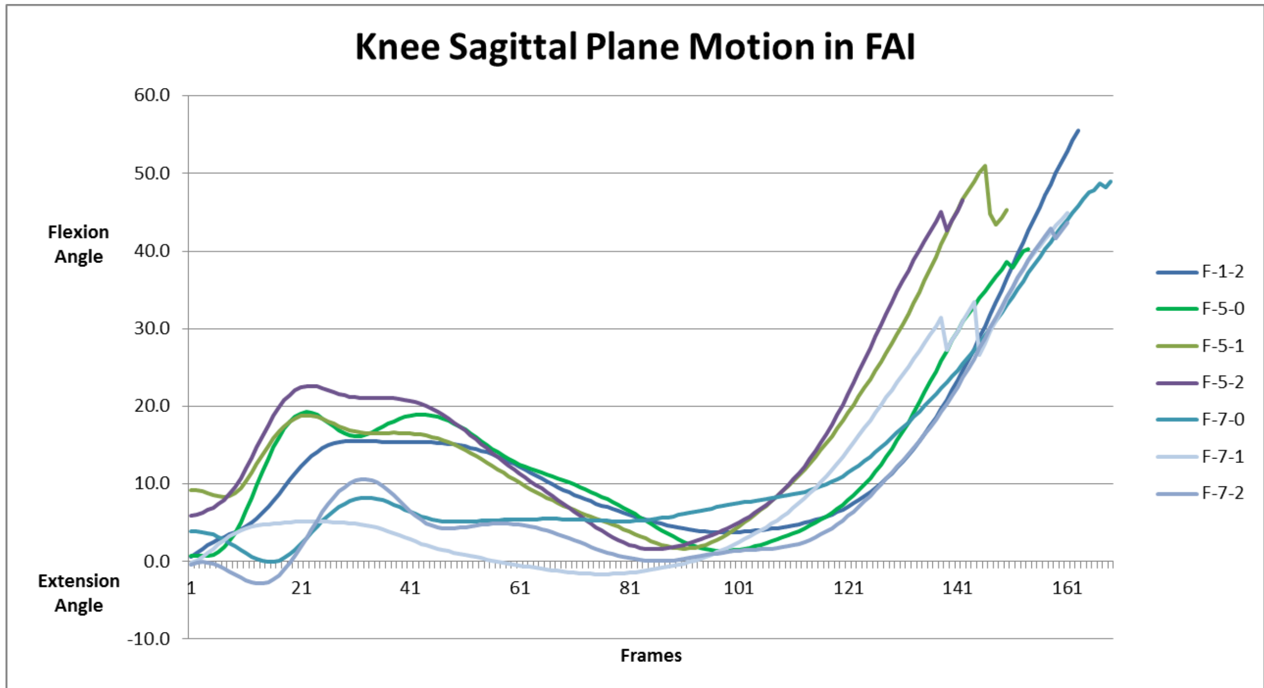
Walking Trials		
Trial	Which foot hit the plate	Walking Pace (s)
1	R / L	
2	R / L	
3	R / L	
4	R / L	
5	R / L	
6	R / L	

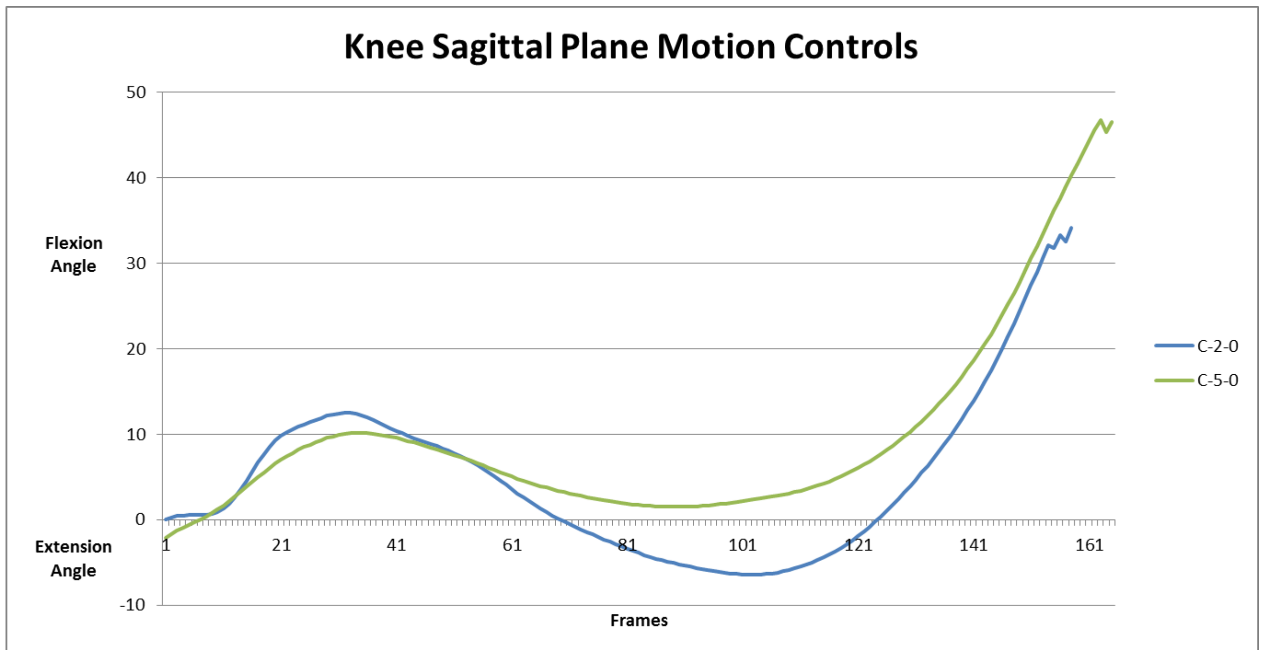
Appendix G. Hip Sagittal Plane Motion during Abnormal Reversals



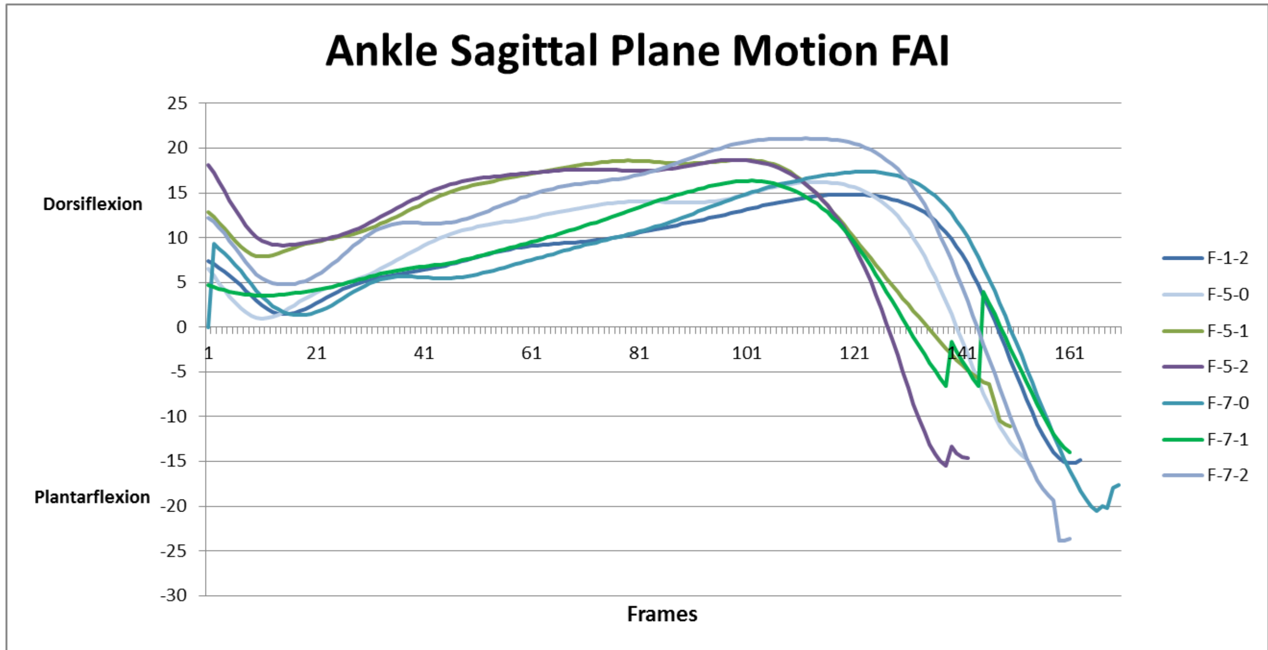


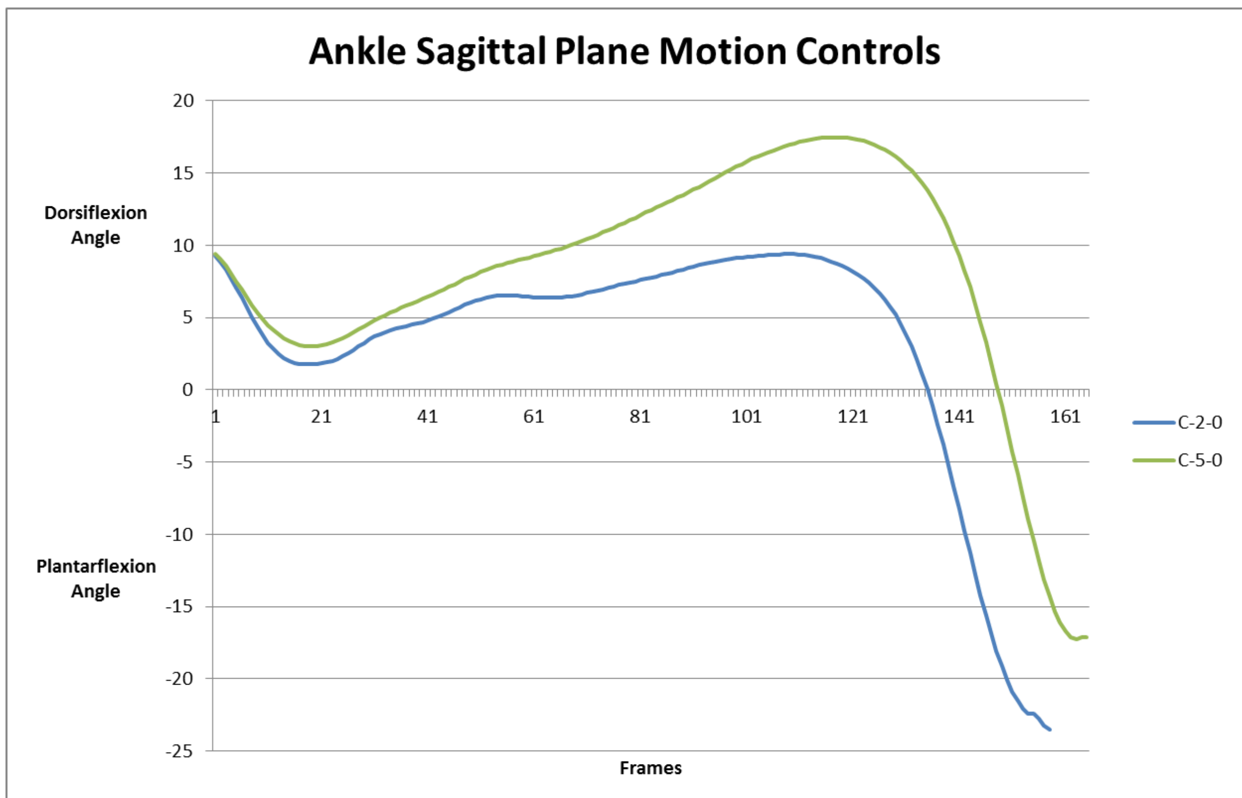
Appendix H. Knee Sagittal Plane Motion during Abnormal Reversals





Appendix I. Ankle Sagittal Plane Motion during Abnormal Reversals





References

1. Ganz R, Parvizi J, Beck M, Leunig M, Notzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. *Clinical orthopaedics and related research.* Dec 2003(417):112-120.
2. Yen YM, Kocher MS. Clinical and radiographic diagnosis of femoroacetabular impingement. *Journal of pediatric orthopedics.* Jul-Aug 2013;33 Suppl 1:S112-120.
3. Zebala LP, Schoenecker PL, Clohisy JC. Anterior femoroacetabular impingement: a diverse disease with evolving treatment options. *The Iowa orthopaedic journal.* 2007;27:71-81.
4. Bedi A, Dolan M, Hetsroni I, et al. Surgical treatment of femoroacetabular impingement improves hip kinematics: a computer-assisted model. *The American journal of sports medicine.* Jul 2011;39 Suppl:43S-49S.
5. Kelly BT, Bedi A, Robertson CM, Dela Torre K, Giveans MR, Larson CM. Alterations in internal rotation and alpha angles are associated with arthroscopic cam decompression in the hip. *The American journal of sports medicine.* May 2012;40(5):1107-1112.
6. Audenaert E, Van Houcke J, Maes B, Vanden Bossche L, Victor J, Pattyn C. Range of motion in femoroacetabular impingement. *Acta orthopaedica Belgica.* Jun 2012;78(3):327-332.
7. Clohisy JC, Knaus ER, Hunt DM, Lesher JM, Harris-Hayes M, Prather H. Clinical presentation of patients with symptomatic anterior hip impingement. *Clinical orthopaedics and related research.* Mar 2009;467(3):638-644.
8. Lamontagne M, Kennedy MJ, Beaule PE. The effect of cam FAI on hip and pelvic motion during maximum squat. *Clinical orthopaedics and related research.* Mar 2009;467(3):645-650.
9. Rylander J, Shu B, Favre J, Safran M, Andriacchi T. Functional testing provides unique insights into the pathomechanics of femoroacetabular impingement and an objective basis for evaluating treatment outcome. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society.* Sep 2013;31(9):1461-1468.
10. Rylander JH, Shu B, Andriacchi TP, Safran MR. Preoperative and postoperative sagittal plane hip kinematics in patients with femoroacetabular impingement during level walking. *The American journal of sports medicine.* Jul 2011;39 Suppl:36S-42S.
11. Hunt MA, Gunether JR, Gilbart MK. Kinematic and kinetic differences during walking in patients with and without symptomatic femoroacetabular impingement. *Clinical biomechanics.* Jun 2013;28(5):519-523.
12. Brisson N, Lamontagne M, Kennedy MJ, Beaule PE. The effects of cam femoroacetabular impingement corrective surgery on lower-extremity gait biomechanics. *Gait & posture.* Feb 2013;37(2):258-263.
13. Kennedy MJ, Lamontagne M, Beaule PE. Femoroacetabular impingement alters hip and pelvic biomechanics during gait Walking biomechanics of FAI. *Gait & posture.* Jul 2009;30(1):41-44.
14. Foucher KC, Schlink BR, Shakoor N, Wimmer MA. Sagittal plane hip motion reversals during walking are associated with disease severity and poorer function in subjects with hip osteoarthritis. *Journal of biomechanics.* May 11 2012;45(8):1360-1365.
15. Levine D, Richards, J., Whittle, M. *Whittle's Gait Analysis.* 5th ed: Churchill Livingstone Elsevier; 2012.
16. Zahiri CA, Schmalzried TP, Szuszczewicz ES, Amstutz HC. Assessing activity in joint replacement patients. *The Journal of arthroplasty.* Dec 1998;13(8):890-895.
17. Martin RL, Philippon MJ. Evidence of reliability and responsiveness for the hip outcome score. *Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association.* Jun 2008;24(6):676-682.

18. Lewis CL, Ferris DP. Walking with increased ankle pushoff decreases hip muscle moments. *Journal of biomechanics.* Jul 19 2008;41(10):2082-2089.
19. Mueller MJ, Sinacore DR, Hoogstrate S, Daly L. Hip and ankle walking strategies: effect on peak plantar pressures and implications for neuropathic ulceration. *Archives of physical medicine and rehabilitation.* Nov 1994;75(11):1196-1200.
20. Kang AC, Gooding AJ, Coates MH, Goh TD, Armour P, Rietveld J. Computed tomography assessment of hip joints in asymptomatic individuals in relation to femoroacetabular impingement. *The American journal of sports medicine.* Jun 2010;38(6):1160-1165.
21. Laborie LB, Lehmann TG, Engesaeter IO, Engesaeter LB, Rosendahl K. Is a positive femoroacetabular impingement test a common finding in healthy young adults? *Clinical orthopaedics and related research.* Jul 2013;471(7):2267-2277.
22. Agricola R, Bessems JH, Ginai AZ, et al. The development of Cam-type deformity in adolescent and young male soccer players. *The American journal of sports medicine.* May 2012;40(5):1099-1106.
23. Kubiak-Langer M, Tannast M, Murphy SB, Siebenrock KA, Langlotz F. Range of motion in anterior femoroacetabular impingement. *Clinical orthopaedics and related research.* May 2007;458:117-124.
24. Byrd JW, Jones KS. Arthroscopic management of femoroacetabular impingement. *Instructional course lectures.* 2009;58:231-239.
25. Naal FD, Miozzari HH, Wyss TF, Notzli HP. Surgical hip dislocation for the treatment of femoroacetabular impingement in high-level athletes. *The American journal of sports medicine.* Mar 2011;39(3):544-550.
26. Nho SJ, Magennis EM, Singh CK, Kelly BT. Outcomes after the arthroscopic treatment of femoroacetabular impingement in a mixed group of high-level athletes. *The American journal of sports medicine.* Jul 2011;39 Suppl:14S-19S.
27. Bizzini M, Notzli HP, Maffiuletti NA. Femoroacetabular impingement in professional ice hockey players: a case series of 5 athletes after open surgical decompression of the hip. *The American journal of sports medicine.* Nov 2007;35(11):1955-1959.
28. Philippon MJ, Ejnisman L, Ellis HB, Briggs KK. Outcomes 2 to 5 years following hip arthroscopy for femoroacetabular impingement in the patient aged 11 to 16 years. *Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association.* Sep 2012;28(9):1255-1261.
29. Lamontagne M, Brisson N, Kennedy MJ, Beaule PE. Preoperative and postoperative lower-extremity joint and pelvic kinematics during maximal squatting of patients with cam femoro-acetabular impingement. *The Journal of bone and joint surgery. American volume.* May 2011;93 Suppl 2:40-45.
30. Hurwitz DE, Hulet CH, Andriacchi TP, Rosenberg AG, Galante JO. Gait compensations in patients with osteoarthritis of the hip and their relationship to pain and passive hip motion. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society.* Jul 1997;15(4):629-635.