■ HIP

Osseous impingement occurs early in flexion in cam-type femoroacetabular impingement

A 4D CT MODEL

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Aims

The aim of this study was to examine the real time *in vivo* kinematics of the hip in patients with cam-type femoroacetabular impingement (FAI).

Patients and Methods

A total of 50 patients (83 hips) underwent 4D dynamic CT scanning of the hip, producing real time osseous models of the pelvis and femur being moved through flexion, adduction, and internal rotation. The location and size of the cam deformity and its relationship to the angle of flexion of the hip and pelvic tilt, and the position of impingement were recorded.

Results

In these patients with cam-type FAI, there was significant correlation between the alpha angle and flexion to the point of impingement (mean 41.36°; 14.32° to 57.95°) (R = -0.5815 and p = < 0.001). Patients with a large cam deformity (alpha angle > 78°) had significantly less flexion to the point of impingement (mean 36.30°; 14.32° to 55.18°) than patients with a small cam deformity (alpha angle 60° to 78°) (mean 45.34°; 27.25° to 57.95°) (p = < 0.001).

Conclusion

This study has shown that cam-type impingement can occur early in flexion (40°), particularly in patients with large anterior deformities. These patients risk chondrolabral damage during routine activities such as walking, and going up stairs. These findings offer important insights into the cause of the symptoms, the mechanisms of screening and the forms of treatment available for these patients.

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Femoroacetabular impingement (FAI) is the result of cam or pincer morphology in the hip. It is present in 23.1% of the general population and 72% of elite soccer players.[1,2] Cam morphology describes a loss of sphericity at the femoral head-neck junction[3] and leads to pain, decreased function, and osteoarthritis (OA).[4,5]

It is thought that the cam lesion is forced into the acetabulum at the limits of flexion (> 90°) and internal rotation,[4,6] resulting in soft-tissue damage. This is based on the clinical reproducibility of symptoms during examination,[6] observational data from surgery,[7] and computer simulated modelling.[8-12] These methodologies, however, fail to visualise the real time *in vivo* biomechanics of the joint, or the interrelated movements of the hip, pelvis and lumbar spine.[13] Thus, our understanding of the pathophysiology of OA in FAI, and the role of cam morphology in the kinematics of the hip is poor. This is reflected in the limited evidence advocating conservative forms of treatment for FAI.[14] Physiotherapy aims to modify the kinematics of the hip to compensate for terminal restriction in the range of movement (ROM).[15] Yet, less than 50% of patients report improvement in symptoms with conservative management,[14] which it seems only benefits patients with mild FAI.[14,15] Surgical correction aims to restore the head-neck offset, but choosing candidates who will benefit remains difficult.[16]

Poor outcomes may be due to the way in which we currently stratify patients for treatment. Cam-type FAI causes damage in impingement which requires movement of the hip,[4,6] yet non-invasive static imaging modalities such as the alpha angle are used to assess the risk factors for impingement.[4,5] Thus it is not possible to base treatment for these patients on a true understanding of the severity of the impingement. A dynamic understanding of the hip joint is required. A number of dynamic imaging methods have been proposed; however, each has limitations. Fluoroscopy has been used to examine the kinematics

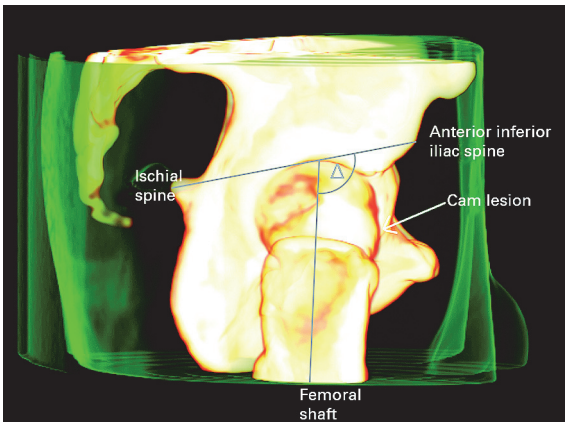


Fig. 1a

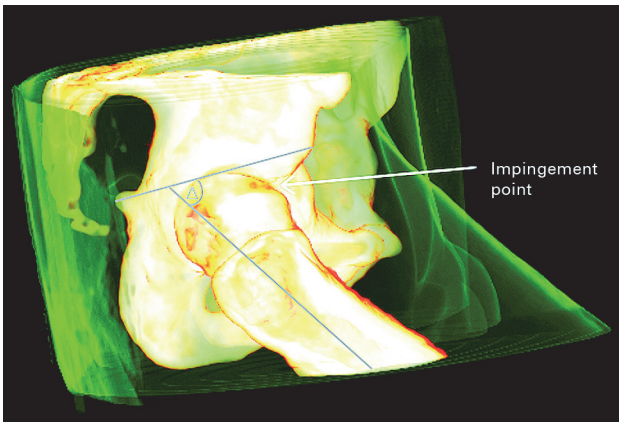


Fig. 1b

3D CT reconstructed models showing a) lateral view of the pelvis and femur showing the angle (Δ) of flexion of the hip, the hip shown is in the supine position and b) the pelvis and femur showing the impingement point during flexion.

of the hip *in vivo*,[17] but is limited by contrast and superimposition issues. Dynamic MRI which offers non-irradiated high soft-tissue contrast, is still in the experimental phase.[18] Finally, 3D CT simulations of the ROM of the hip and the site of impingement have been described, offering promising insights into the kinematics of the hip and pre-operative planning.[8-12] However, they have not been validated with actual *in vivo* movement and the site of the impingement.

Recent advances in CT have allowed real time dynamic sequences to be developed. These are sometimes referred to as 4D CT scans and can be used pre-operatively to assess the location of the impingement.[19] However, this methodology is yet to be used to determine the effect of cam morphology on the kinematics of the hip and impingement.

The aims of this study were to use 4D CT scanning to examine real time *in vivo* kinematics of the hip in patients with cam-type FAI, and to investigate the point at which cam engagement occurs during flexion in these patients.

Patients and Methods

This study involved symptomatic patients undergoing pre-operative assessment before arthroscopic surgery of the hip. All were under the care of the senior author (SG-J). Patients underwent 4D dynamic CT scanning of one or both hips as part of routine pre-operative investigations. Dynamic CT scans were performed with the hip undergoing the flexion adduction internal rotation (FADIR) test passively. A radiographer trained in the examination of the hip flexed the hips to 90°, with as much internal rotation and adduction as passive movement or the constraints of the scanner would allow, or until a symptomatic response was elicited.

All scans were performed using the same Toshiba Aquillion One CT scanner (Toshiba Medical Systems, Zoetermeer, The Netherlands). Image acquisition settings were; 0.5 second tube rotation time, total scan time of 8.5 seconds, 100 kVp, matrix 512 × 512, scan field of view (FOV) maximum of 350 mm (display FOV varied depending on the size of the patient), maximum tube current of mA 40 (varied depending on the size of the patient), 17 axial volumes produced with 0.5 mm thickness at 0.5 mm apart in 0.5 second intervals using soft-tissue sharp reconstruction, effective exposure time product mAs of 20, dose length product (DLP) varied depending on the size of the patient but ranged from 250 to 300 per hip (to reduce DLP a manual exposure modulation process was used). Toshiba volume rendering software (Toshiba Medical Systems) produced a 3D model of the components of the bone (Fig. 1), which can be viewed and analysed in a 4D animation.

Dynamic 4D CT scan images were exported as Digital Imaging and Communications in Medicine and manually analysed using OsiriX Software (version 6.0.2 64 Bit, Pixmeo, Geneva, Switzerland) by a single observer (CA). An alpha angle threshold of 60° was used to define a cam deformity.[20] Scans were excluded if there was evidence of pincer morphology, with a centre edge angle > 39°[21] or OA (Kellgren-Lawrence[22] grade > 0). Multiplanar 3D reconstructions were produced as radial slices around the axis of the femoral neck at 30° intervals allowing cam morphology to be quantified by measuring the alpha angle on each radial slice at the 11, 12, 1, 2, and 3 o'clock positions[23] (Fig. 2). An alpha angle of 60° was used to define the presence of a small cam deformity and 78° for a large cam deformity. These values are based on the work of Agricola et al[20] showing that an alpha angle > 78° had the highest discriminative ability for the development of OA.

Flexion of the hip was defined as the angle formed between a line connecting the most anterior point of the anterior inferior iliac spine with the most posterior point of the ischial spine, and the line of the femoral shaft at its midpoint. This angle was measured both with the patient in the resting supine position (S) (Fig. 1a) and at the point of furthest flexion (FF) during the FADIR test. Pelvic tilt was defined as the angle formed between the line connecting the most anterior point of the anterior inferior iliac spine with

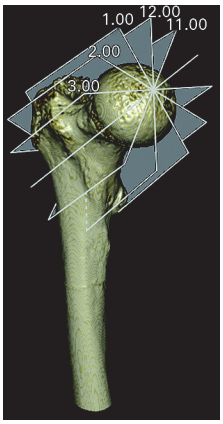


Fig. 2a

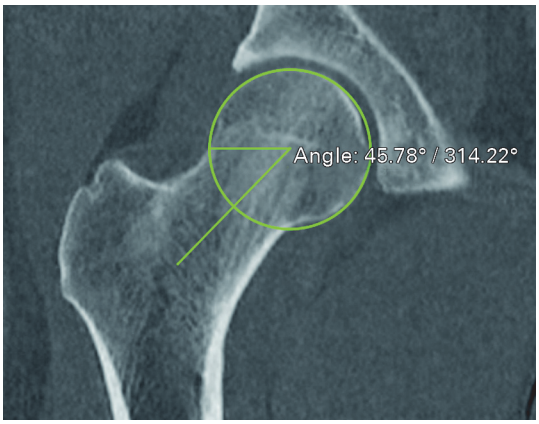


Fig. 2b

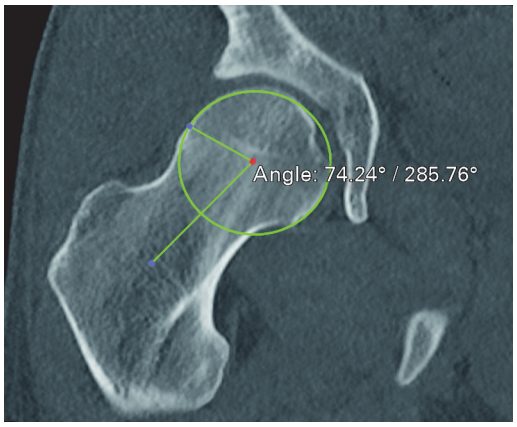


Fig. 2c

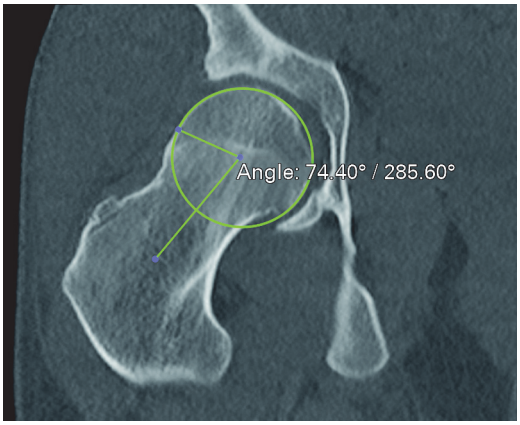


Fig. 2d

Images showing a) radial slice measurement of alpha angles showing clock face positions; b) 12 o'clock; c) 1 o'clock; and d) 2 o'clock position.

the most posterior point of the ischial spine, and the horizontal. The impingement point (IP) was defined as the point at which any part of the cam lesion made contact with the acetabulum on the 4D reconstructions (Fig. 1b). The range of flexion was defined as the change from S to the IP or FF. The anatomical position of impingement was determined using standardised clockface nomenclature[8,10] (Figs 3a and 3b). The study had ethical approval from the institutional review board of The Manor Hospital Oxford where patients had their scans taken.

Statistical analysis. Descriptive statistics were performed. The data were examined for distribution using Kernel Density plots.[24,25] Groups, as determined by the presence of a cam deformity and its size and location were tested for significant difference using the unpaired *t*-test. The relationship between the alpha angle and range of flexion or pelvic tilt was quantified using linear regression and expressed as a correlation coefficient (R). Statistical software StataMP 14.0 (College Station, Texas) was used for analysis and significance was set at $p < 0.05$.

The primary observer (CA) repeated all measurements of ten randomly selected hips one month after their original readings. A second observer (SF) performed the same measurements. The reproducibility was measured using intraclass correlation coefficients (ICCs) and the smallest detectable difference (defined as mean change ± 1.96 × standard deviation of the change).[26] Intra-observer ICC ranged from 0.971 to 0.997, and inter-observer ICC ranged from 0.941 to 0.993 (Table I).

Results

A total of 83 4D dynamic CT scans were identified from 50 patients (83 hips). There were 22 men (39 hips) and 28 women (44 hips) with a mean age of 39 years (18 to 60). Movement was limited by a symptomatic response in 21 hips (25.3%), and by restrictions of the scanner in 17 hips (20.5%). The morphology of the femoral head-neck junction was normal in 33 hips (39.8%); 50 (60.2%) had cam morphology, 22 (26.5%) of which had a large cam deformity. No cam morphology was detected at 11 o'clock in any patient (Table II).

Effect of cam morphology on hip flexion. In patients with cam morphology, significant correlation was seen between the alpha angle and a mean range of flexion from S to IP of 41.36° (14.32° to 57.95°) and from S to FF of 48.17° (24.51° to 62.24°) (Table II). A 2 o'clock alpha angle nega-

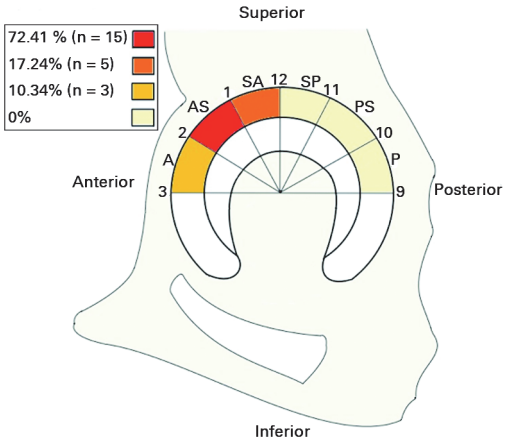


Fig. 3a

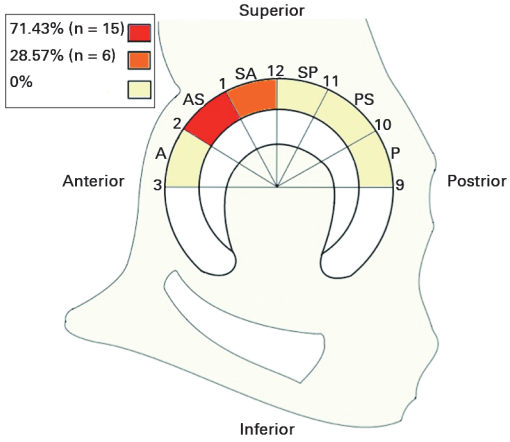


Fig. 3b

Contact of the impingement point on the acetabular rim. Regions of interest are denoted as: anterior (A) between 3 and 2 o'clock, anterosuperior (AS) area between 2 and 1 o'clock, superoanterior (SA) between 1 and 12 o'clock, superoposterior (SP) area between 12 and 11 o'clock, posterosuperior (PS) area between 11 and 10 o'clock, and posterior (P) area between 10 and 9 o'clock: a) occurrence of impingement point on the acetabular rim in patients with cam morphology at a) 2 and 3 o'clock positions and; b) 12 and 1 o'clock positions.

Table I. Reproducibility data for all measurements

	Intra-observer		Inter-observer	
	ICC	**SDD**	**ICC**	**SDD**
Alpha angle	0.991	5.12	0.972	5.98
Hip flexion	0.98	2.91	0.955	4.14
Pelvic tilt	0.997	0.95	0.993	1.35
Impingement point	0.971	3.72	0.941	4.81

ICC, intra-class correlation coefficients; SDD, smallest detectable difference

tively correlated with the range of flexion from S to IP where R = -0.6358 and p = < 0.001 (Fig. 4), and with the range of flexion from S to FF where R = -0.5815 and p = < 0.001 (Fig. 5), such that the larger the alpha angle the lower the range of flexion from S to IP and FF (Table III).

Effect of cam morphology on pelvic tilt. Those with cam morphology had a significantly greater degree of pelvic retroversion during flexion from S to FF than those with normal femoral head-neck junction morphology (p = < 0.001) (Table II). There was significant correlation in those with cam morphology, between the alpha angle and the degree of pelvic tilt during flexion of the hip from S to FF (mean 3.57°; 2.24° to 6.38°) (Table II). At 2 o'clock, the alpha angle negatively correlated with flexion from S to FF where R = 0.7019 and p = < 0.001, such that the larger the alpha angle the greater the degree of pelvic retroversion (Table III).

Effect of the size and location of the cam lesion on hip flexion. Patients with a large cam deformity had a significantly lower range of flexion from S to IP (mean 36.30°; 14.32° to 55.18°) than patients with a small cam deformity (mean 45.34°; 27.25° to 57.95°) (p = < 0.001) (Table IV). Those with a large cam deformity at 2 and 3 o'clock positions had a significantly lower range of flexion from S to IP (mean 32.25°; 14.32° to 45.79°) than those with a large cam deformity at the 12 and 1 o'clock positions (mean 40.51°; 27.92° to 55.18°) (p = < 0.001) (Table V), such that a larger and more anterior cam lesion significantly reduced flexion prior to impingement.

Effect of the size and location of the cam lesion on pelvic tilt. Patients with a large cam deformity had significantly more retroversion during flexion to FF (mean 4.36°; 2.91° to 6.38°) than those with a small cam deformity (mean 3.06°; 2.24° to 4.53°) (p < 0.001) (Table IV). A large cam deformity had no significant impact on pelvic retroversion during flexion.

Discussion

Our aims were to use 4D CT scanning to examine the real time *in vivo* kinematics of the hip in patients with cam morphology, and to investigate the cause of symptoms in cam-type FAI. It is currently thought that OA in FAI is due to engagement of a cam lesion with the acetabulum at the limits of flexion and internal rotation of the hip resulting in soft-tissue damage.[4,27]

Table II. Measurement and *t*-test p-values for alpha angle, range of flexion of the hip and pelvic tilt from the supine position (S) to the impingement point (IP) and point of furthest flexion (FF) for patients with normal femoral head-neck junction morphology (alpha angle < 60°) and those with cam morpology (alpha angle > 60°). Values expressed as mean (range)

		Normal femoral head-neck junction morphology (alpha angle < 60°)	Cam morphology (alpha angle > 60°)	p-value (*t*-test)
Cohort characteristics	n	33	50	N/A
	Age (yrs)	38.91 (19.03 to 55.87)	39.95 (19.61 to 60.60)	N/A
	Male	5	34	N/A
	Female	28	16	N/A
Alpha angle	11 o'clock	35.16° (27.41° to 41.35°)	38.15° (29.12° to 83.89°)	N/A
	12 o'clock	37.54° (29.59° to 44.70°)	45.43 (33.89° to 87.89°)	N/A
	1 o'clock	43.96° (36.08° to 58.42°)	66.62 (38.55° to 106.21°)	N/A
	2 o'clock	49.41° (36.18° to 58.54°)	73.50 (35.32° to 122.02°)	N/A
	3 o'clock	42.58° (30.15° to 56.38°)	62.07 (31.43° to 94.07°)	N/A
Range of hip flexion	S to IP	N/A	41.36° (14.32° to 57.95°)	N/A
	S to FF	46.24° (24.41° to 61.07°)	48.17° (24.51° to 62.24°)	0.297
Range of pelvic tilt	S to IP	N/A	0.67° (-1.93° to 3.06°)	N/A
	S to FF	0.17° (-3.84° to 5.12°)	3.57° (2.24° to 6.38°)	< 0.001*

*statistically significant
N/A, not applicable

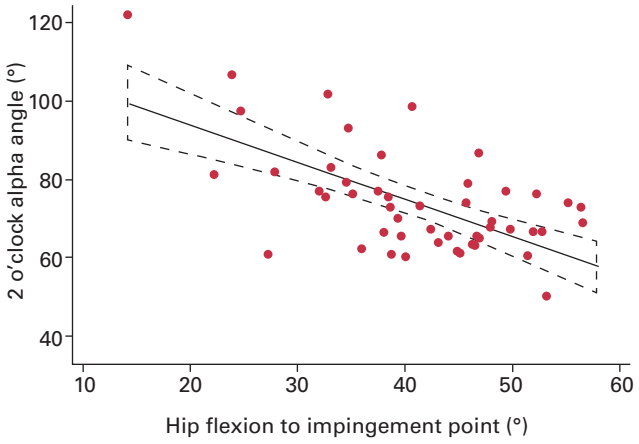


Fig. 4

Scatterplot of alpha angle at the 2 o'clock position in those with cam morphology *versus* flexion of the hip to the impingement point with 95% confidence intervals.

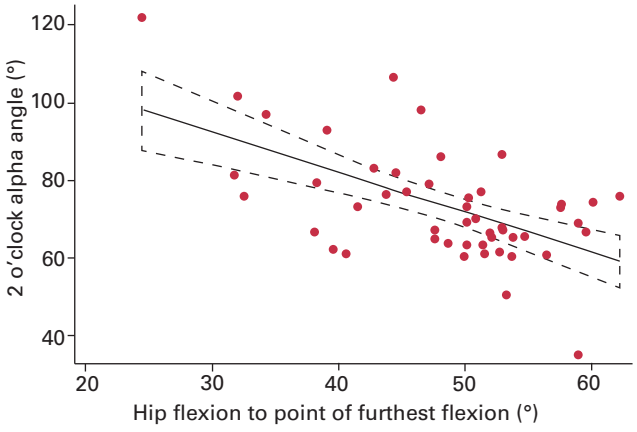


Fig. 5

Scatterplot of alpha angle at the 2 o'clock position in those with cam morphology *versus* range of flexion of the hip from supine to the point of furthest flexion with 95% confidence intervals.

More recently, computer simulated modelling studies[8-12] have proposed numerical values for the kinematics of the hip in FAI, quoting the impingement point at 90° to 100° of flexion.[9-11] However, in these studies the pelvis has been fixed and the femoral movement isolated and pre-defined. They, therefore, fail to simulate anatomical functional compound movement or to take account of any soft-tissue involvement that may limit or influence movement. Many of these systems are used for surgical planning and decision-making. Tannast et al,[9] however, found that their computer simulation consistently overestimated the ROM.

We found that the size and location of the cam lesion have a significant impact on the kinematics of the hip. The larger and more anterosuperior the lesion the sooner the point of impingement is in the arc of flexion. Importantly however, impingement may be taking place much earlier than previously anticipated, at angles of flexion of about 40°. Patients with a large cam deformity (alpha angle > 78°) at the 2 and 3 o'clock positions are impinging 10° earlier than those with a small cam deformity (alpha angle between 60° and 78°), in as low as 30° of flexion (Table V).

These findings may have significant implications for our understanding of the pathophysiology of chondrolabral damage and OA in FAI. Our results suggest that patients with a large cam deformity anterosuperiorly may be impinging throughout most of the arc of flexion. Indeed,

Table III. Relationship between alpha angle and range of flexion of the hip and pelvic tilt from the supine position (S) to the impingement point (IP) and furthest point of flexion (FF) in patients with normal femoral head-neck junction morphology (alpha angle < 60°) and cam morphology (alpha angle > 60°)

		Normal femoral head-neck junction morphology				Cam morphology			
		Hip flexion		Pelvic tilt		Hip flexion		Pelvic tilt	
Alpha angle position	Range of flexion	R value	p-value	R value	p-value	R value	p-value	R value	p-value
11 o'clock *vs*:	S to IP	N/A	N/A	N/A	N/A	0.136	0.347	0.020	0.889
	S to FF	-0.121	0.503	-0.102	0.571	0.123	0.395	-0.066	0.928
12 o'clock *vs*:	S to IP	N/A	N/A	N/A	N/A	0.135	0.351	-0.276	0.053
	S to FF	0.213	0.184	-0.212	0.236	-0.581	0.144	0.322	0.005*
1 o'clock *vs*:	S to IP	N/A	N/A	N/A	N/A	-0.224	0.119	-0.196	0.173
	S to FF	-0.160	0.373	-0.047	0.794	0.060	0.677	0.482	< 0.001*
2 o'clock *vs*:	S to IP	N/A	N/A	N/A	N/A	-0.636	< 0.001*	0.094	0.516
	S to FF	0.213	0.235	-0.202	0.261	-0.581	< 0.001*	0.702	< 0.001*
3 o'clock *vs*:	S to IP	N/A	N/A	N/A	N/A	-0.422	0.0023*	0.085	0.558
	S to FF	0.067	0.712	-0.357	0.041*	-0.407	0.003*	0.573	< 0.001*

* statistically significant, linear regression
R value, correlation coefficient; N/A, not applicable

Table IV. Measurement and *t*-test p-values for alpha angle, range of flexion of the hip and pelvic tilt from the supine position (S) to the impingement point (IP) and furthest point of flexion (FF) for patients with a small cam deformity (alpha angle 60° to78°) and those with a large cam deformity (alpha angle > 78°). Values expressed as mean (range)

		Small cam deformity (alpha angle 60° to 78°)	Large cam deformity (alpha angle > 78°)	p-value (*t*-test)
Cohort characteristics	n	28	22	N/A
	Age (yrs)	40.53 (9.61 to 60.60)	39.34 (22.92 to 57.41)	N/A
	Male	17	16	N/A
	Female	11	6	N/A
Alpha angle	11 o'clock	37.85° (29.97° to 45.22°)	38.53° (29.12° to 83.89°)	N/A
	12 o'clock	41.82° (35.31° to 53.52°)	50.02° (33.89° to 87.89°)	N/A
	1 o'clock	56.29° (40.36° to 76.45°)	79.76° (38.85° to 106.21°)	N/A
	2 o'clock	65.36° (35.32° to 77.17°)	83.87° (60.29° to 122.02°)	N/A
	3 o'clock	55.97° (31.34° to 70.68°)	69.83° (46.09° to 94.07°)	N/A
Range of hip flexion	S to IP	45.34° (27.25° to 57.95°)	36.30° (14.32° to 55.18°)	< 0.001*
	S to FF	50.58° (32.57° to 62.24°)	45.09° (24.51° to 60.2°)	0.018*
Range of pelvic tilt	S to IP	0.62° (0.00° to 2.31°)	0.61° (-1.93° to 3.06°)	0.962
	S to FF	3.06° (2.24° to 4.53°)	4.36° (2.91° to 6.38°)	< 0.001*

* statistically significant
N/A, not applicable

they are probably impinging in functional movements such as walking or going up stairs, where flexion is 40° and 70° respectively.[28] These results may help to explain the pathophysiology behind the findings of Agricola et al[20] in their work on the 'Cohort Hip and Cohort Knee' and Chingford cohorts. They found that although cam morphology existed at alpha angles > 60°, a large cam deformity with alpha angle > 78° had the highest discriminative ability for the development of OA at five- and 19-year follow-up.[20] This suggested that a large cam deformity confers a high risk of progression to end-stage OA and joint arthroplasty in these patients. Our findings would suggest that this might be due to an earlier point of impingement. Soft-tissue damage in FAI occurs at the point of, and during, mechanical abutment.[4,10,27] Early impingement would result in an increased degree of mechanical abutment, and therefore potentially more damage with the passage of time.

The potential clinical use of these findings is extensive, having large implications for how we stratify the risk in patients and decide upon treatment. Our findings suggest that patients with a large cam deformity anterosuperiorly are likely to be causing the most chondrolabral damage.

Even if the impingement point is delayed in the flexion arc by physiotherapy or modification of movement[14,15] these patients still risk significant chondrolabral damage. Non-surgical intervention for patients with a large cam deformity should perhaps instead focus on limitation of activity and avoiding high flexion. Arguably, these patients should be offered early reconstructive surgery. These findings could potentially form a screening tool, and be used with other prognostic measures of OA such as biomarkers (Table VI).

Pelvic tilt is an essential dynamic component of posture and kinematics in normal activity.[29] Its role in FAI remains poorly understood, but almost a quarter of patients with symptomatic FAI have pain in the sacroiliac joint.[30] We found that the larger and more anterosuperior the cam lesion the greater is the degree of pelvic retroversion during

Table V. Measurement and *t*-test p-values for alpha angle, range of flexion of the hip and pelvic tilt from the supine position (S) to the impingement point (IP) and furthest point of flexion (FF) for patients as determined by the location and size of the cam morphology. Values expressed as mean (range)

		Large cam deformity (alpha angle > 78°)		
		12 o'clock or 1 o'clock	2 o'clock or 3 o'clock	p-value (*t*-test)
Cohort characteristics	n	12	10	N/A
	Age (yrs)	39.94 (27.00 to 57.40)	38.71 (22.92)	N/A
	Male	8	9	N/A
	Female	4	1	N/A
Alpha angle	11 o'clock	35.96° (29.12° to 41.19°)	41.60° (30.87° to 88.39°)	N/A
	12 o'clock	54.27° (33.89° to 86.98°)	44.93° (36.14° to 87.89°)	N/A
	1 o'clock	88.37° (80.19° to 106.21°)	69.43° (38.55° to 102.46°)	N/A
	2 o'clock	74.88° (60.29° to 86.62°)	94.66° (79.12° to 122.02°)	N/A
	3 o'clock	65.83° (46.09° to 80.67°)	74.62° (59.23° to 94.07°)	N/A
Range of hip flexion	S to IP	40.51° (27.92° to 55.18°)	32.25° (14.32° to 45.79°)	0.039*
	S to FF	49.57° (31.81° to 60.12°)	39.72° (24.51° to 48.10°)	0.008*
Range of pelvic tilt	S to IP	0.21° (-1.93° to 0.9°)	1.20° (0.03° to 3.06°)	0.031*
	S to FF	4.36° (3.00° to 5.81°)	4.36° (2.91° to 6.38°)	0.996

*statistically significant
N/A, not applicable

Table VI. Risk matrix and treatment screening tool for the location and size of the cam deformity on flexion prior to impingement point. Values given are mean flexion prior to impingement

		Cam location	
		2 o'clock or 3 o'clock	12 o'clock or 1 o'clock
Cam size (alpha angle)	> 78°	High risk (32.25°)	Moderate risk (40.51°)
	60° to 78°	Moderate risk (44.95°)	Low risk (46.32°)

flexion (mean 3.57°). Although statistically significant, the clinical significance of this relatively small value could be questioned. However, Rylander et al[31] found that successful osteochondroplasty for FAI increased the ROM in normal gait by only 2.9°. Moreover, Ross et al[8] found that small increases in pelvic retroversion could reduce the occurrence of anterior cam impingement, suggesting that even small changes in ROM can have large clinical significance.

There are several reasons why our results might differ from those of previous computer-simulated studies.[8-12] We investigated the kinematics of the hip during the FADIR test, as opposed to during full ROM. Moreover, we were measuring unrestricted functional movement in the presence of the soft tissues. This is in contrast to previous models that make assumptions based on simplistic simulations of single vectors of movement around a point within a stationary pelvis, with some translation when impingement occurs. Wassilew et al[19] used 4D CT to focus on the contact point in impingement, and commented on the kinematics in full flexion and abduction, as opposed to the kinematics prior to impingement, making comparison with our study difficult.

We found that the location of impingement was most commonly the anterosuperior acetabular rim, which agrees with previous reports.[10,11] The ICC was > 0.9 for all measurements, showing that our methodology was highly reproducible. This is better than that of Ross et al[8] of > 0.87, and similar to that of Bedi et al[11] of 0.9.

A limitation of this and previous CT-based kinematic studies is that they do not account for the soft tissues. The constraints of the scanner limited the analysis of the terminal range of flexion of the hip and pelvic tilt. Moreover, the size of the 4D reconstruction was limited by the 140 mm Z-axis cover of the scan, such that the choice of consistent anatomical landmarks for measurement was limited. Furthermore, 4D CT involves a high dose of radiation, about three times the dose of a routine CT examination of the pelvis, which may limit its suitability for certain patients. This high dose of radiation also meant that testing for impingement in additional movements, such as abduction, or posterior impingement, is not possible. A final limitation of the study was that it was performed on symptomatic patients undergoing surgery and we do not know whether the findings would be reproduced in asymptomatic people with cam morphology.

In conclusion, this study has shown that large cam morphology at 2 and 3 o'clock positions results in much earlier impingement than was previously thought. The findings offer insights into the cause of symptoms in patients with cam morphology and may help stratify these patients for surgery. The 4D CT scanning of the hip is a valuable research and clinical tool. The software required is available as an upgrade to standard CT scanners, and so has high clinical applicability. However, further investigations into alternative 4D scanning platforms, such as MRI, may offer more information about the dynamic impact on soft tissue of cam morphology.



Take home message:

- Impingement in flexion in cam-type FAI may occur much earlier than previously thought.

- The 4D CT scan has shown itself to be useful as both a research and clinical decision-making tool.

Author contributions:
S. Fernquest: Study design, Data analyses, Writing the paper.
C. Arnold: Data analyses, Writing the paper.
A. Palmer: Data analyses, Writing the paper.
J. Broomfield: Data analyses, Writing the paper.
J. Denton: Collection of data.
A. Taylor: Study design, Writing the paper.
S. Glyn-Jones: Study design, Patient care, Writing the paper.

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