3.5 Kinematic evaluation of total hip arthroplasty with various bearing materials

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Introduction

Early failure mechanisms in total hip arthroplasty (THA) have included component loosening [16,20,32,42], material failure [3,17], infection [15], dislocation [7], osseous fracture [21,22], and neurovascular injury [41]. More recently, failure secondary to premature polyethylene wear, particularly associated with modular acetabular components, has become prevalent [3,17]. Only limited research has been conducted relating wear with the in vivo motions and forces occurring at the hip joint. Researchers have utilized both telemetry [1,2,9,14,42] and mathematical modeling [4,8,24,25,33,35,39,40] to predict in vivo forces across the hip joint. Data collected from these studies has been utilized in hip joint simulation devices to predict polyethylene wear patterns of acetabular components in THA [5,36,37,43] Unfortunately, polyethylene wear seen with simulated THA has not always produced wear patterns seen with retrieval analyses [5,12,30] Since discrepancies exist between wear patterns of simulated versus actual retrieval specimens, it can be assumed that variations exist between simulated and actual in vivo hip joint kinematics. These variations may be related, at least in part, to surgical alterations in the supporting soft tissue structures of the hip or to biomechanical alterations related to prosthetic geometry.

More recently, video fluoroscopy has been used to determine the in vivo kinematics of the hip joint [11,23,26]. Initially, these studies assumed the motions of the normal and implanted hip joints would differ since many of the soft-tissue supporting structures of the hip joint are altered during THA. These previous fluoroscopic studies confirmed that the femoral head may separate from the medial aspect of the acetabular component during both gait and when performing an active hip abduction-adduction activity [11,23,26]. It has also been reported that subjects having a metal-on-metal (MOM) THA experience less femoral head separation than subjects having a metal-on-polyethylene (MOP) THA [23]. The objective of this report is to perform a comparative analysis of hip kinematics in a large number of THA subjects implanted with differing femoral head and acetabular liner bearing materials to determine if the incidence and magnitude of hip separation in THA subjects is affected by the type of bearing material utilized.

Methods

The present report consists of a summation analysis of eight individual studies performed in our research laboratory over the last five years. Overall, 195 subjects implanted THA were analyzed under fluoroscopic surveillance while performing either gait on a level treadmill or an abduction-adduction maneuver. Institutional Review Board approval was obtained before commencement of each individual study. Inclusion criteria included only those subjects with hip arthroplasties considered highly clinical successful (Harris Hip Scores[18] > 90 points) without pain or functional deficits. None of the subjects reported any signs of hip instability and none had suffered a dislocation postoperatively. No patient walked with a detectable limp and all could actively abduct their operated hips against gravity without difficulty. Average follow-up periods for the eight individual studies ranged from three to 26 months.

All THA subjects were implanted with one of four articular bearing surface combinations. These articular bearing surface combinations included metal-on polyethylene (MOP), metal-on-metal (MOM), alumina ceramic-on-polyethylene (AOP), or alumina ceramic-on-alumina ceramic (AOA) THA designs. The number of subjects tested during each of the three activities tested (swing phase of gait; stance phase of gait; abduction-adduction maneuver) is listed in Table 1. Due to the multi-center nature of this summation analysis, the arthroplasty procedures were performed by multiple surgeons.

Abduction / Adduction Maneuver

- **25 MOP / 10 AOP / 10 AOA**

Gait: Stance Phase

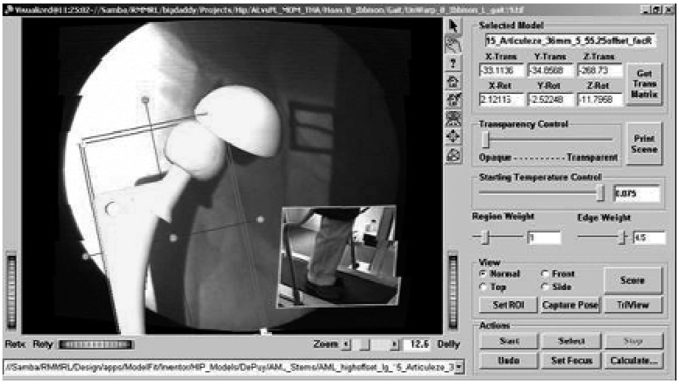
- **10 MOP / 40 MOM / 10 AOP / 10 AOA**

Gait: Swing Phase

- **10 MOP / 50 MOM / 10 AOP / 10 AOA**

Table 1: Number of subjects analyzed during each activity tested.

Those subjects tested during and abduction- adduction maneuver were analyzed in a stationary position with fluoroscopic visualization in the frontal plane. Those analyzed during gait performed normal walking while on a level treadmill. During the swing-phase of gait, the initial position analyzed occurred just after toe-off. Then throughout the swing-phase of gait, every third fluoroscopic video image was analyzed, including the image just before heel-strike. The number of images analyzed for each patient depended upon their stance phase of gait (average = 8 frames/subject). All subjects were analyzed using a computer automated three-dimensional (3D) model fitting process [10,27,38] to determine the distance between the femoral head and the medial aspect of the acetabular component (Fig. 1). Initially, 3D computer assisted



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Starting Temperature Control: 0.075
Region Weight: 1
Edge Weight: 45
View: ● Normal ○ Top ○ Front ○ Side
Zoom: 12.6

Figure 1: Example of the 3D automated model-fitting process in which the computer assisted design (CAD) models of the femoral head, stem and the acetabular component are overlaid onto the 2D fluoroscopic image to determine three-dimensional position of the prosthetic components.

design (CAD) models of the acetabular component and proximal portion of the femoral component are entered into the two-dimensional (2D) fluoroscopic scene. Using an interactive approach, the operator, assisted by the computer algorithm, fits the 3D CAD model of the acetabular component onto the 2D fluoroscopic image of the acetabular component. Thereafter, the 3D CAD model of the proximal femoral component is precisely overlayed onto the 2D fluoroscopic image of the femoral component. The acetabular and femoral head components are then grouped together and rotated to a pure frontal view. The distance from the medial most aspect of the acetabular component and the medial aspect of the femoral head was then measured to determine if separation of the femoral head from the acetabular component had occurred (Fig. 2).

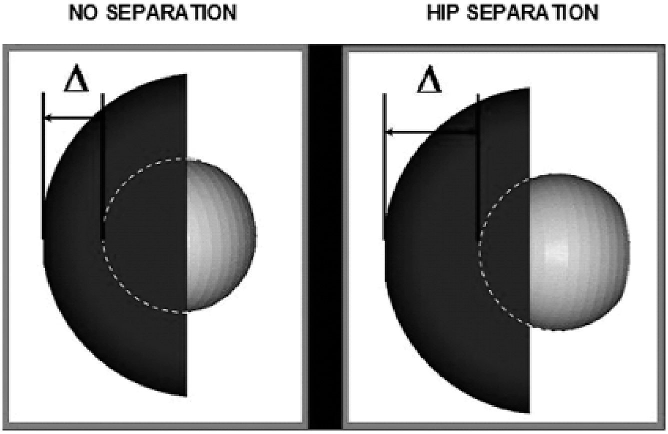

Figure 2:
Upon completion of the three-dimensional overlay process, the acetabular and femoral head components are grouped together and rotated to a pure frontal view. The distance ( ) from the medial most aspects of the acetabular component and femoral head is then measured to determine for the presence of hip separation.

An extensive error analysis was conducted using three different methods to verify the accuracy of the 3D model-fitting process. Initially, a mechanical apparatus that allows for two prosthetic components to be translated and rotated relative to each other was used. The known versus predicted implant positions were then compared [10]. Using this process, the relative rotational error was < 0.75 degrees and translational error < 0.5 mm. Next, the two components were similarly placed at known positions in space relative to each other. The fixated components were then rotated and translated while under dynamic fluoroscopic surveillance. The average error for this dynamic analysis was < 0.5 mm in translation and < 0.5 degrees in rotation [38]. Finally, the two components were surgically implanted into a fresh cadaver. Ninety relative orientations (translations and rotations) were captured using video fluoroscopy. An Opto-Track system (Northern Digital, Inc., Waterloo, Ontario, Canada), was used to determine the ground-truth (known position of each component relative to a fixed reference frame). Then the model fitting process was used to predict relative orientation of the implanted components. The error of all 90 trials was

< 0.5 mm in translation and < 0.5 degrees in rotation. Therefore, femoral head separation was predicted to occur if the femoral head-acetabular component distance was greater than our error threshold of 0.5 mm [27].

Results

The magnitudes of hip separation during an abduction-adduction maneuver are demonstrated in (Table 2). The greatest amount of hip separation was observed in those with a MOP THA (average 2.3mm; maximum 6.4mm; Fig. 3) and the least occurred in subjects implanted with an AOA THA (average 0.6mm; maximum 0.7mm). The incidence of hip separation greater than 0.5mm during an abduction-adduction activity was high in all implant designs ranging from 80-100% (Table 3a). This high incidence of hip separation persisted in MOP THA subjects when assessing the incidence of hip separation greater than 1.0mm (92%), but was much less in AOP THA patients (30%) and totally absent in those implanted with an AOA THA (Table 3b).

The magnitudes of hip separation during the stance phase of gait are shown in Table 4. Similar average magnitudes of hip separation were observed in MOP, MOM, and AOP THA subjects (1.1 - 1.3mm). The average hip separation was the least in subjects implanted with an AOA THA who exhibited an average hip separation value of 0.3mm which is less than the 0.5mm error value of the analytical process utilized. The incidence of hip separation greater than both 0.5mm and 1.0mm during the stance phase of gait varied substantially among the different THA designs tested but was greatest in MOP THA subjects and least in those with an AOA THA (Table 5a, 5b).

	AVERAGE (mm)	**MAXIMUM (mm)**
MOP THA	**2.3**	**6.4**
AOP THA	**1.1**	**3.2**
AOA THA	**0.6**	**0.7**

Table 2:
Magnitudes of hip separation occuring during an abduction-adduction maneuver.

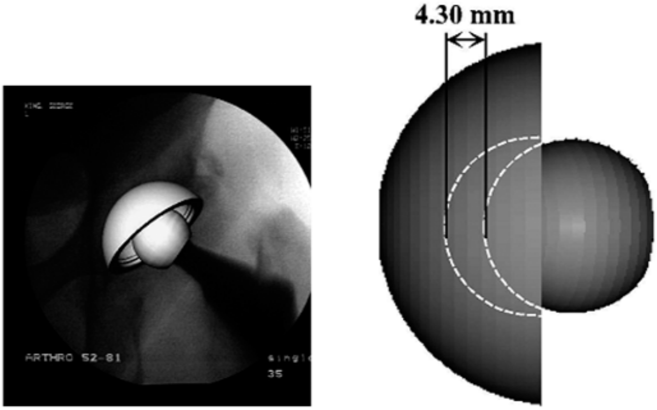

Figure 3:
Overlaid fluoroscopic image (left) and computer analysis of a subject implanted with a MOP THA demonstrating 4.30 mm of hip separation during an abduction-adduction maneuver.

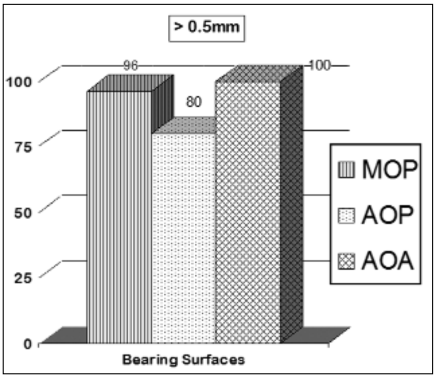

Table 3a:
Incidence of hip separation >0.5mm occurring during an abduction-adduction maneuver.

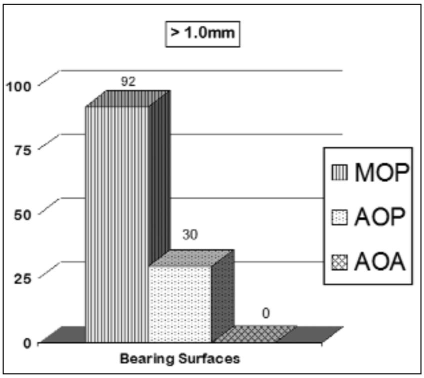

Table 3b:
Incidence of hip separation >1.0mm occurring during an abduction-adduction maneuver.

	AVERAGE (mm)	MAXIMUM (mm)
MOP THA	**1.2**	**2.8**
MOM THA	**1.1**	**3.1**
AOP THA	**1.3**	**7.4**
AOA THA	**0.3***	**0.6**

Table 4:
Magnitudes of hip separation occuring during the stance phase of gait.

***< Error Value of 0.5 mm**

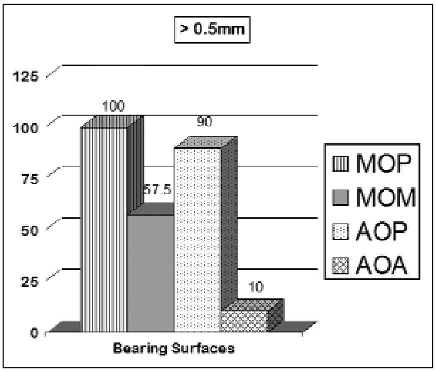

Table 5a:
Incidence of hip separation <0.5mm occurring during the stance phase of gait.

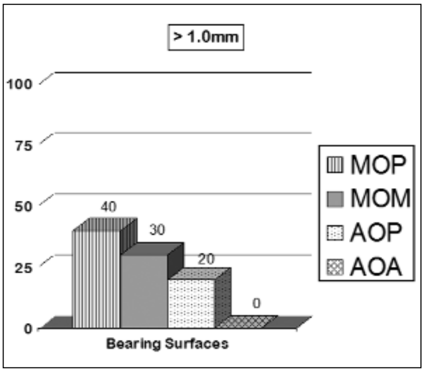

Table 5b:
Incidence of hip separation >1.0mm occurring during the stance phase of gait.

The magnitudes of hip separation during the swing phase of gait are demonstrated in (Table 6). Again, the greatest average values of hip separation were observed in those with a MOP THA (average 2.1mm; maximum 3.1mm) and the least occurred in subjects implanted with either a MOM or AOA THA (average separation 0.9mm and 1.0mm respectively). The incidence of hip separation greater than 0.5mm during the swing phase of gait was greater than 50% in all implant designs ranging from 50-100% (Table 7a, 7b). This incidence of hip separation greater than 1.0mm varied from 10-80%, being greatest in those implanted with a MOP THA (80%) and least in those with an AOP THA (10%).

	AVERAGE (mm)	**MAXIMUM (mm)**
MOP THA	**2.1**	**3.1**
MOM THA	**0.9**	**2.9**
AOP THA	**1.2**	**7.0**
AOA THA	**1.0**	**2.2**

Table 6:
Magnitudes of hip separation occuring during the swing phase of gait.

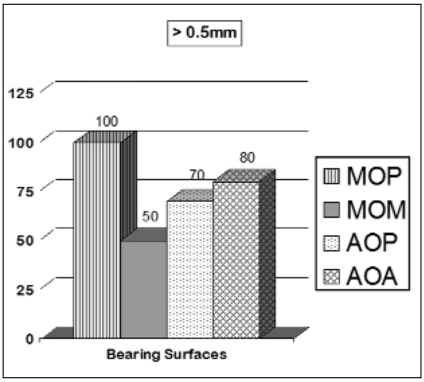

Table 7a:
Incidence of hip separation >0.5mm occurring during the swing phase of gait.

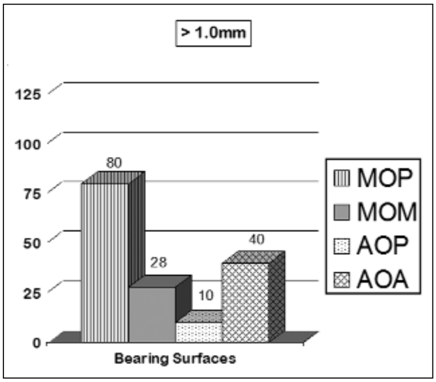

Table 7b:
Incidence of hip separation >1.0mm occurring during the swing phase of gait.

One cohort of patients in this multi-center analysis implanted with MOM THA was tested twice at two different time intervals. When tested early postoperatively (3-6 months postoperatively), no hip separation greater than the error value of 0.5mm was observed. This same group was re-analyzed at a mean follow-up period of two years and demonstrated an average separation value of 1.6mm, suggesting the magnitude and incidence of hip separation may increase over time.

The typical separation pattern observed is separation of the femoral head from the medial aspect of the acetabular component while maintaining contact with the polyethylene superolaterally. In this situation, the femoral head is therefore often pivoting on the peripheral rim of the polyethylene liner in extreme cases of hip separation.

Discussion

In an initial study analyzing subjects while performing a hip abduction-adduction maneuver, femoral head separation from the acetabulum was not observed in subjects with normal hip joints or those implanted with a constrained THA, but occurred in all subjects implanted with an unconstrained MOP THA [11]. Similar findings of a high incidence of hip separation were observed in an initial evaluation subjects having a MOP THA during gait [26]. These findings resulted in the hypothesis that patients implanted with an unconstrained MOP THA are subjected to inertial forces that produced separation of the femoral head from the acetabular component during several different dynamic activities. This evidence necessitated further analyses to determine if the incidence and magnitude of hip separation was affected by the type of bearing surface material utilized in primary THA.

In the normal hip joint, retention of the femoral head within the acetabulum is provided by numerous supporting soft tissue structures, including the fibrous capsule, acetabular labrum, ligament of the head of the femur (LHF), and the iliofemoral, ischiofemoral, pubofemoral, and transverse acetabular ligaments. During a THA, the LHF is surgically removed. Additionally, a portion of the remaining supporting soft tissue structures are transected or resected to facilitate surgical exposure. It is therefore logical to assume that the kinematics of the implanted hip may vary from the normal hip since the stabilizing soft tissues are altered at the time of operation. Hip separation is potentially detrimental and may play a role in complications observed with THA today including hip instability, premature polyethylene wear, and prosthetic loosening.

The role of hip separation in instability following THA is unclear and deserves further evaluation. Coventry [7] reviewed a group of 32 patients who suffered late dislocations following THA. He postulated that stretching of the supporting soft tissue structures (i.e., pseudocapsule) over time and extremes of range of motion may lessen soft tissue constraints and allow for late dislocation. Continued study of our present patient group is indicated to see if the amount of hip separation increases over time, suggesting a role in late hip instability.

The presence of hip separation may contribute to premature polyethylene wear due to increased shear forces placed on the polyethylene material during impulse loading cycles. The impulse generated by the collision of two objects has been shown to potentially compromise the structural integrity of mechanical components [40]. A simplified kinetic analysis indicated a predicted average increase in hip forces of 289.5 Newtons due to hip separation and the subsequent reduction of the femoral head back into the acetabulum resulting in the development of impulse loading conditions [11]. This increased load may potentially compromise implant fixation, resulting in premature component loosening. Additionally, during separation, the femoral head typically remains in contact and pivots on the polyethylene liner superolaterally, creating higher eccentric loads which increase the potential of premature polyethylene wear in this region.

Yamaguchi et al. [44] performed a three-dimensional evaluation of wear vectors in 104 retrieved acetabular components and found that 31 (30%) demonstrated multidirectional wear vectors which were highly variable among differing specimens. The maximum linear wear in retrieved liners with multi-directional wear vectors was greater than in those with unidirectional wear patterns. They hypothesized that the multidirectional wear pathways observed may result in accelerated polyethylene wear due to increased shear forces. Pooley and Tabor [34] reported that when high density polyethylene is subjected to unidirectional sliding, the molecules tend to align along the direction of sliding, resulting in lowering of the coefficient of friction, potentially reducing wear of the material. With multi-directional wear patterns, they observed the shear stresses are increased and wear rates accelerate. Further study is required to define what role hip separation may play in creation of multidirectional wear vectors and accelerated polyethylene wear.

While hip simulator experimentation has been valuable in providing information on polyethylene wear, in vivo wear has proven to be a complex and multi-factorial process [6,12,13,29,30,37]. Data from hip simulators has not always equated well with retrieval studies with variations seen in wear rates and patterns as well as debris particulate size. These inconsistencies are likely related to multiple factors such as variations in the level of polyethylene oxidation, the rigidity of component fixation, the strength of periacetabular support [28], and hip kinematics of test versus retrieval specimens. Incorporation of hip separation into hip wear simulators may allow more accurate replication of in vivo conditions. The significance of the findings in this study is supported by the recent work of Nevelos et al. [31] who conducted an analysis to assess the significance of hip micro-separation in AOA THA. Using a hip simulator, micro-separation of the femoral head from the acetabular component during gait was incorporated into the simulated hip motion patterns. Their simulated specimens were then compared to in vivo clinical retrievals of the same implant design. They determined that contact between the femoral head and the peripheral rim of the acetabular insert as a result of micro-separation produced damage to the components which was similar to the damage observed in retrieval studies. They also observed similar grain boundary fracture wear mechanisms. Therefore, they concluded that micro-separation during simulator tests reproduced, for the first time, clinically relevant wear rates, patterns, debris and mechanics compared with THA retrievals.

Data collected from telemetric hip studies has demonstrated an increased force magnitude peak typically is present immediately after heel strike compared to the force magnitude at toe-off [1,2,19,42]. It has been hypothesized that this increase in force is due to muscle contraction. Based on the present fluoroscopic evaluations, we theorize that the increased force seen immediately after heel strike results, at least in part, from the femoral head translating back into the acetabular component at heel strike, producing impulse loading conditions. This hypothesis is supported by the work of Taylor et al [42] who conducted a telemetric study in which two proximal femoral replacements were instrumented to determine axial forces at two sites within the prosthesis. When analyzing consecutive steps during normal gait, they observed that the force just after heel strike and immediately before toe-off were often of differing magnitudes. Again it can be hypothesized that the increased force they observed immediately after heel strike could be attributed to hip joint separation resulting in generation of impulse loading conditions between the femoral head and acetabular component. Similar force patterns have been observed in the telemetric hip studies of Bergmann et al [1,2].

The reduced incidence of hip separation in subjects with AOA THA, and to a lesser extent, those implanted with a MOM THA, may be related to the narrow tolerance bands and high surface finishes of AOA and MOM THA components which allow for a thin film of fluid to become entrapped between the femoral head and acetabular liner. Because of the defined finish diametral trial clearances and the rheological properties of synovial fluid under physiological kinetics and kinematics, a thin micro-electric hydro-dynamic lubrication film can be present. The tighter radial tolerances of the AOA and MOM THA designs do not allow for discontinuities or voids between the femoral head and acetabular liner, which in turn, creates a fluid film cohesion with higher radial tension. Due to the increased wetability of ceramic surfaces, this film can effectively connect and constrain the femoral head to the acetabular liner during gait. This cohesive force only needs to sufficiently overcome the inertial forces causing the leg to separate from the body during the swing phase of gait. In MOP and AOP THA, larger diametral clearances between the femoral head and polyethylene liner exist. Additionally, wetability of polyethylene is less. We therefore hypothesize that the cohesiveness of the lubricating film of MOP and AOP THA is reduced, allowing hip separation to occur. The reduced incidence and magnitude of hip separation in subjects having an AOA or MOM THA leads to the hypothesis that patients implanted with these designs are subjected to more favorable mechanical environments and more uniform wear kinematics during gait.

Although hip separation was initially only found (and thought to only occur) during the swing-phase of gait, a high incidence and magnitude of hip separation during the stance-phase of gait was also observed (Fig. 4). It appears that during the stance-phase of gait, the acetabular component slides away from the femoral head from 66% of stance-phase to toe-off. In the normal hip, as the momentum of the pelvis moves forward, the capsular and ligamentous structures of the hip joint help maintain the femoral head within the acetabular component, even while the lagging foot remains planted on the ground through toe-off. We hypothesize that disturbance of capsular and ligamentous structures during THA allows the femoral head to separate from the acetabulum as the pelvis thrusts anteriorly along with the contralateral leg as it moves anteriorly through swing-phase and the lagging foot remains on the ground, completing stance-phase through to toe-off.

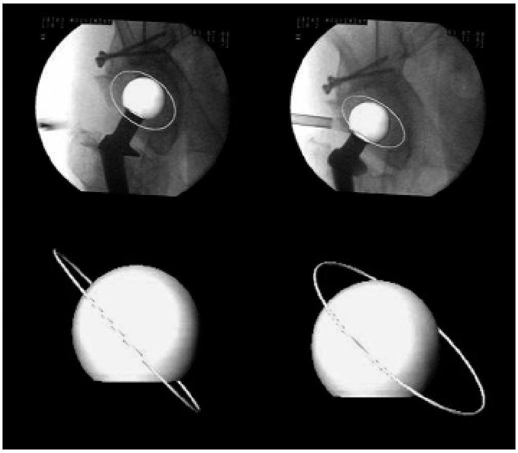

Figure 4:
Fluoroscopic (top) and computer analysis (bottom) images of a subject implanted with an AOP THA who experienced 7.4 mm of femoral head separation (right images), occurring from mid-stance to toe-off of the stance-phase of gait.

Summary

The present study demonstrates that femoral head separation from the acetabular component can occur under weight-bearing conditions during gait and an abduction-adduction activity in subjects implanted with various designs of THA. The incidence and magnitude is greatest in those with MOP THA and least in subjects implanted with an AOA THA. Potential detrimental effects resulting from hip joint separation include premature polyethylene wear, component loosening secondary to impulse loading conditions and late hip instability. The reduced hip separation observed in AOA THA subjects is likely related to the increased wetability of this material as well as reduced diametral clearance typically seen in hard-on hard bearings which results in a cohesive fluid film lubrication regime.

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