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EFFECTS OF EPISODIC SUBLUXATION EVENTS ON THIRD BODY INGRESS AND EMBEDMENT IN THE THA BEARING SURFACE

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Abstract

In total joint arthroplasty, third body particle access to the articulating surfaces results in accelerated wear. Hip joint subluxation is an under-recognized means by which third body particles could potentially enter the otherwise closely conforming articular bearing space. The present study was designed to test the hypothesis that, other factors being equal, even occasional events of femoral head subluxation greatly increase the number of third body particles that enter the bearing space and become embedded in the acetabular liner, as compared to level walking cycles alone. Ten metal-on-polyethylene hip joint head-liner pairs were tested in a multi-axis joint motion simulator, with CoCrMo third body particles added to the synovial fluid analog. All component pairs were tested for two hours of level walking; half also were subjected to twenty intermittent subluxation events. The number and location of embedded particles on the acetabular liners were then determined. Subluxation dramatically increased the number of third body particles embedded in the acetabular liners, and it considerably increased the amount of scratch damage on the femoral heads. Since both third body particles and subluxation frequently occur in contemporary total hip arthroplasty, their potent synergy needs to be factored prominently into strategies to minimize wear.

Keywords

Hip arthroplasty; impingement; mechanical testing; subluxation; third body wear

Introduction

In total joint arthroplasty, third body particle migration into the bearing space results in accelerated wear. Third body particles are defined as debris originating other than from normal articulation between the femoral head and acetabular liner. Metallic debris predominates as third body particles, as demonstrated by a retrieval study of polyethylene liners involving quantification of embedded particles (Lundberg et al., 2007a); examples of metallic third body particles include porous ingrowth beads (Dowd et al., 2000; Najjar et al., 2000) or metal

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particles from the implants (Hirakawa et al., 2004; Huk et al., 1994; Kim et al., 2005; Lewis, 1997), from trochanteric reattachment fixation (Amstutz and Maki, 1978; Bronson, 1976; Hop et al., 1997), or from surgical instruments (Mackay et al., 2000). Third body particles can also originate from hydroxyapatite (Bauer et al., 1994; Bloebaum et al., 1997; Willie et al., 2000), bone (Que and Topoleski, 2000), or bone cement (Isaac et al., 1992; Joshi et al., 2001). Once they gain access to the space between the articulating components, third bodies can directly abrade both the acetabular and femoral head bearing surfaces. Third bodies can also cause indirect damage through this abrasive process; the roughening of a femoral head, such as can occur by third body scratching, can increase the wear rate of a polyethylene liner.

Tribologically, even minimal scratching of a metallic articular surface can result in severe wear rate increase of polyethylene (Dowson et al., 1987). Third body particles embedded in polyethylene acetabular components are a well-documented finding in retrieval studies (Bloebaum et al., 1997; Isaac et al., 1992; Kim et al., 2005; Lundberg et al., 2007a; Shon et al., 2005; Sychterz et al., 1996), and are therefore suspected of contributing to the intra-cohort variability of wear (Joshi et al., 2001; Orishimo et al., 2003), even for bearing combinations that have relatively low cohort-average wear rates.

Although no broadly accepted testing standards yet exist for simulating third body wear, both hip simulator (Bragdon et al., 2003) and pin-on-disc (Davidson et al., 1994; McKellop et al., 1981; Que and Topoleski, 2000) tests of UHMWPE against metal have demonstrated that scratching of the metal surface and dramatically increased polyethylene wear can occur after the introduction of third body particles into the lubricant fluid. Other protocols have placed third body particles directly in the articulating surface (Davidson et al., 1994; McKellop et al., 1981; McKellop and Rostlund, 1990; McNie et al., 2000), or have indirectly simulated third body effects using abrasion-tumbling, emery abrasion, or discrete scratching of femoral heads (Affatato et al., 2005; Barbour et al., 2000; Endo et al., 2001; McKellop et al., 1999; Wang et al., 1998); many of these studies also demonstrated increased polyethylene wear resulting from third body effects.

Third body debris present in the joint fluid migrates ubiquitously throughout communicative compartments of the peri-articular environment (Hop et al., 1997). However, metal-on-polyethylene total hip replacements normally operate with their bearing surfaces in very close conformity (fluid film thickness on the order of tenths of micrometers (Jalali-Vahid et al., 2001) if indeed not direct contact). Given that typically embedded third body particles often have sizes up into the hundreds of micrometers (Lundberg et al., 2007a), the question arises as to how such debris manages to reach wear-critical regions near the pole of the bearing space.

Subluxation potentially provides a mechanism for entry of third body particles into the bearing space between the articulating surfaces. Subluxation necessarily occurs shortly after impingement between the femoral neck and the acetabular rim, quite apart from whether or not there is frank dislocation of the components. Subluxation is presumably a commonplace occurrence in THA, as retrieval studies have documented a high prevalence of damage (up to 66% of specimens) on the rim of acetabular liners, indicative of femoral neck impingement (Hall et al., 1998; Isaac et al., 1992; Jasty et al., 1997; Murray, 1992; Shon et al., 2005; Wroblewski, 1985; Yamaguchi et al., 2000; Yamaguchi et al., 1999). A recent computational fluid dynamics model has provided theoretical evidence that, during THA subluxation, joint fluid is actively drawn into the space that opens between the head and liner (Lundberg et al., 2007b), providing access to wear-critical regions of the bearing surface near the pole of the liner. Third body particles suspended in this fluid would presumably be convected into the articulating surfaces by this mechanism. Additional evidence to support this paradigm was subsequently provided by a retrieval study (Lundberg et al., 2007a), in which acetabular liners with impingement damage were found to be substantially more likely to have embedded debris

than were liners without impingement damage, and where the likelihood of embedded debris presence increased with the severity of impingement damage to the liner.

The present study was designed to physically test the hypothesis that occasional events of femoral head subluxation would increase the number of third body particles that enter the bearing space and become embedded in the acetabular liner, as compared to for level walking cycles alone. While intuitively plausible, this hypothesis has almost never been directly articulated (Shon et al., 2005), nor has it ever been objectively tested.

Methods

A cemented smooth femoral stem (Summit™ Basic, DePuy Orthopaedics, Warsaw, IN) was potted into a femoral fixture at 12° adduction. A metallic acetabular shell (Duraloc™, DePuy) was potted into an acetabular fixture at 30° tilt and 0° anteversion. For each of ten replicate experiments, a fresh 28 mm femoral head (Articul/Eze™, DePuy) and a matching fresh unconstrained UHMWPE acetabular liner (Duraloc™ Enduron, DePuy) were attached to the stem and shell, respectively.

The femoral and acetabular fixtures included a capture ring, around which a hip capsule surrogate consisting of 3 mil (76.2 µm) thin plastic sheeting (Papermart, Los Angeles, CA) was secured (Figure 1). The femoral fixture also included auxiliary features to facilitate circulation of fluid (and suspended third body particles) within the peri-articular space enclosed by the hip capsule surrogate. These features consisted of a nozzle for capsule fluid entry proximally, multiple holes along the bottom of the fixture for fluid exit, and smooth diagonal shrouding which discouraged third body particle settling and, which along with fins attached to the shroud, helped direct the particles to the fluid exit holes.

The specimens were then placed in a multi-axis joint motion simulator (Figure 2) actuated by an MTS 858 Bionix materials testing machine (MTS Systems Corp., Eden Prairie, MN). The joint motion simulator included a pair of concentric yokes that allowed control of rotations about flex/extension and ab/adduction axes, in addition to the load and endo/exorotation (about the vertical axis) available with the standard axial-torsional Bionix system. This motion simulator device used rotary actuators (Model SS 2A 1V, MTS) and rotary variable differential transformers (RVDTs) (Model 605-0001, MTS) attached to a custom-built frame. The femoral fixture was attached to an x-y table mounted atop of the MTS load cell. The x-y motion of this table was measured by linear potentiometers (Model B100K, Alpha Products, Inc., Oxnard, CA). Axial motion of the joint motion simulator device was measured by the MTS's linear actuator's linear variable differential transformer (LVDT).

A synovial fluid analog was added to the system after securing the hip capsule surrogate around the femoral and acetabular fixtures. This analog fluid consisted of an 84.2% glycerin-15.8% water mixture by weight. This mixture had a viscosity of approximately 100 centipoise at 25° C, representative of human synovial fluid (Mazzucco et al., 2002; Walker et al., 1970), and was chosen over less-viscous bovine calf serum for that reason. To help keep the third body debris suspended, this fluid was actively circulated throughout the test by means of a peristaltic pump (Figure 1, Figure 2). The total fluid volume used for each specimen, within the hip capsule surrogate and the pump and hoses combined, was approximately 400 ml. The fluid was changed for each head-liner pair.

Each head-liner pair was first preconditioned by six minutes of level walking. The level walking waveforms determined by Kotzar et al. (1991) were converted to axial loads and rotational degrees-of-freedom for the MTS joint simulator (Figure 3). Body weight was assumed to be 620 N. Cycle frequency was 1 Hz.

After preconditioning, twenty-five grams of metallic third body particles were then injected into the system, where they circulated along with the synovial fluid analog. These particles consisted of CoCrMo beads (PREP® F-75 Alloy Powder, Advanced Specialty Metals, 121 Inc., Nashua, NH) sieved to -140/+325 mesh (44 – 106 µm size range). This particular CoCrMo alloy is the one specified in ASTM F75-01 for use in surgical implants (ASTM, 2001), and the size range of the particles straddled the median particle size of 69 µm found in a recent retrieval study of embedded acetabular debris (Lundberg et al., 2007a).

The walking cycles were then continued for two hours (7200 cycles). In five of the ten head-liner pairs tested, twenty flexion subluxation events were interspersed in this two-hour period, with one subluxation event before every six minutes of walking (Figure 4). Impingement between the acetabular liner and the femoral neck collar occurred at approximately 10.5° before the extremum of the commanded flexion arc. These subluxation events caused an average separation of 3.5 mm between the head and liner centers of rotation. Axial load during the subluxation event was held at 100 N.

After the test period was completed, the components were retrieved, and the number and location of embedded particles on the acetabular liner were determined. The liner was first washed of any non-embedded debris, and then photographed. The digital image of the acetabular bearing surface was analyzed using a graphical user interface (Lundberg, 2006), created in Matlab v6.5.1 (The MathWorks Inc., Natick, MA). The image analysis program recorded the number of particles and their locations. Also, the femoral head was visually examined and photographed, for qualitative assessment of scratching.

Results

The acetabular liners that experienced intermittent subluxations had a sixteen-fold increase in the average number of embedded third body particles, as compared to acetabular liners that experienced walking cycles alone ($p = 0.017$, 1-tailed two-sample Student's t-test with unequal variance) (Figure 5). The walking-plus-subluxation group had an average of 334 particles embedded per liner (range, 145–710; standard deviation, 220), whereas the walking only group had an average of only 21 particles embedded per liner (range, 7–40; standard deviation, 13).

The femoral heads in the walking-plus-subluxation group (Figure 6a) were dramatically more heavily scratched than those in the walking-only group (Figure 6b). The walking-plus-subluxation specimens had hundreds of scratches, most of which followed curvilinear, roughly elliptical motion paths, appearing as if a particle had repeatedly scratched the head, with slight offsets, over multiple walking cycles, creating a family of more-or-less parallel scratches. By contrast, the walking-only specimens (Figure 6b) had as few as three such families per head, apparently associated with scratching by isolated third body particles. For the subluxation specimens, the scratches appeared rougher (Figure 6a), which could have been due to either earlier particle ingress (allowing more time for more scratch cycles to occur or for the scratch to expand in size with multiple duty cycles), or due to larger third body particles being able to enter the bearing space. Evidence of embedded particles shifting around between load cycles was also apparent, both from the slight scratch offsets between load cycles (Figure 6b), and in a collection of a large number of parallel scratches seen on one femoral head (from the level-walking group) despite only seven embedded particles being detected after the test (Figure 6c).

Discussion

Under otherwise identical conditions, subluxation during hip simulator testing greatly increased the number of third body particles that became embedded in the acetabular bearing surface. Adding only twenty intermittent subluxation events to two hours of level walking

(7200 cycles) in a hip simulator resulted on average in a sixteen-fold increase in the number of third body particles found to be embedded in the acetabular liner. The subluxation events also greatly increased the severity of femoral head scratching.

For the purpose of documenting a cause/effect relationship in an experimentally practicable time frame, this testing protocol involved a level of third body challenge in excess of what would typically be encountered *in vivo*. The particle load, i.e., the number of particles per unit fluid volume, was greatly supra-physiologic, to increase the chance that particles would be in a position to quickly enter the space between the articulating surfaces. Presumably, similar effects could have been achieved for more modest particle concentration challenges, with the much larger number of motion cycles occurring physiologically. Davidson et al. (1994) found that adding small (1.48 μm) titanium particles to the lubricant fluid in a UHMWPE-on-CoCrMo pin-on-disc test increased the polyethylene wear after 500,000 cycles, but only when the order-of-magnitude particle concentration was 10,000 particles per ml fluid or higher. As a point of comparison, in the present experiment the number of particles per unit fluid volume was approximately 3 times higher and the particle size was nominally 50 times larger, although only about 1/70th as many duty cycles were involved. The purpose-designed fluid circulation system used in the present experiment further aided in having particles available near the head-liner interface, for possible entry. The fluid circulation system also reduced the amount of particle settling, a technical problem noted by Davidson et al. (1994). (Particle settling seemingly would be an even more difficult issue with lower-viscosity fluids typically used in laboratory wear simulators.) As a point of reference, a recent retrieval study of acetabular liners with visible embedded debris detected an average of 42 particles per liner, at an average *in situ* time of 147 months (Lundberg et al., 2007a).

There is ample documentation of third body particles embedded in retrieved acetabular liners (Bloebaum et al., 1997; Isaac et al., 1992; Kim et al., 2005; Lundberg et al., 2007a; Shon et al., 2005; Sychterz et al., 1996). Lundberg et al. (2007a) found that acetabular liners with impingement damage were significantly more likely to have embedded debris, and that liners with higher grades of impingement damage were increasingly more likely to have embedded debris. However, Shon et al. (2005) found no significant correlation between the presence of rim damage (indicative of impingement) and the amount of embedded debris in the liner. Isaac et al. (1992) showed an acetabular liner that had both impingement damage (“rim wear”) and particles on the liner surface (“cement ingress”), but they did not explicitly connect these two phenomena. Sychterz et al. (1996) found that polyethylene liners with embedded debris corresponded to femoral heads that had almost 70% higher mean surface roughness than those without embedded debris, and that wear of the debris-embedded polyethylene liners was significantly higher than for otherwise similar liners in that study. Also, Kim et al. (2005) found that increased surface roughness of the femoral head and presence of embedded debris in the acetabular liner were both associated with increased wear, and that the surface roughness of femoral components increased due to metal transfer onto ceramic femoral heads.

Previous wear simulator studies involving particle addition to the lubricant fluid have demonstrated metal scratching and increased polyethylene wear. Bragdon et al. (2003) tested both conventional and highly crosslinked UHMWPE liners against CoCrMo heads in a hip simulator in which third body debris was suspended within the lubricant fluid and the fluid recirculated within the simulator station. Aluminum oxide particles increased the incremental wear rate of both types of polyethylene, although bone cement particles with barium sulfate did not. Multidirectional scratching of the femoral heads, similar to that in the present specimens, was observed. Que and Topoleski (2000) found that particles of polymerized bone cement (both with and without barium sulfate) or of bone, when added to the lubricant fluid, scratched CoCrMo specimens articulating in a pin-on-disc test against UHMWPE, with severe scratches on the metal being observed with as few as 2700 cycles. Davidson et al. (1994)

increased the wear of a UHMWPE pin articulating on CoCrMo by adding titanium particles to the lubricant fluid, with the amount of wear increasing with particle concentration, provided that a threshold concentration was achieved. McKellop et al. (1981) added unpolymerized PMMA powder (with barium sulfate) to the lubricant fluid for tests involving an UHMWPE pin articulating against discs of different metals. Titanium 6-4 showed severe, immediate scratching, with the test being terminated at 500 cycles. Other metals (316 stainless steel, multiphase CoNiCrMoTi alloy, cobalt chrome alloy, nitrided titanium 6-4), however, resisted damage up to 57,000 cycles.

The present hip simulator experiment convincingly demonstrated that subluxation facilitates third body particle entry into the bearing space, and it provides physical confirmation of the results of related computational fluid dynamics (Lundberg et al., 2007b) and retrieval (Lundberg et al., 2007a) studies. Debris embedded in the acetabular liner at wear-critical locations subsequently scratches the femoral head, which can lead to increased wear of the acetabular liner. While third body effects are broadly acknowledged pro forma, contemporary surgical practice and contemporary implant designs have as yet taken disproportionately little direct action to eliminate this potentially supervening wear mechanism. Third bodies unfortunately are a fact of life in contemporary THA, due to the desirability of component modularity and of non-cemented fixation. Subluxation is also a fact of life, as is demonstrated by the multiple retrieval studies showing impingement damage on the acetabular liner. Thus, the potent synergy of third body particles and hip subluxation demonstrated in this study needs to be borne prominently in mind when considering mechanisms of wear, especially for outlier patients most prone to osteolysis. This is an unpleasant truth not only for historical and contemporary bearing couples, but also for contemplated future innovations. For example, design features which further increase the impingement-free range of motion, quite apart from concern regarding frank dislocation, may merit consideration. Hopefully, work to clarify the nebulous linkage between idealized laboratory tribology studies and clinically-manifest outlier wear/osteolysis will help make the third body wear problem more directly visible to the orthopaedic surgical community, a necessary first step towards outlier minimization.

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Figure 1. Schematic of femoral and acetabular fixtures, capsule surrogate, shroud, and fluid circulation for hip simulator third body ingress testing.

Figure 2.
Total hip arthroplasty preparation in multi-axis joint simulator actuated by an MTS 858 Bionix materials testing machine, and including third body particle circulation.

Figure 3.
Hip joint level walking cycle from Kotzar et al. (1991), as adapted to the multi-axis joint simulator.

Figure 4.

THA subluxation event for studying third body particle ingress. A) Hip simulator applying the subluxation configuration, with hip capsule and shroud removed for clarity. B) Oblique and C) *en face* views of joint surface gap opening during subluxation.

Figure 5.

Location and count of embedded third body particles for acetabular liners tested in a hip simulator for A) walking-plus-subluxation cycles, and for B) walking-only cycles. The superior direction is vertical, and the impingement point is at $\sim 90^\circ$. (Location dots are not to scale per the particle sizes.)

Figure 6.

Scanning electron micrographs of representative regions of femoral head scratching, for components tested in a hip simulator with third body particles in the synovial fluid analog. The superior direction is upward. A) Femoral head from the walking-plus-subluxation cycles test group, from the specimen having the median number of third body particles for that test group embedded in its mating acetabular liner. B) Femoral head from the walking-only cycles test group, again from the specimen having the median number of third body particles for that test group embedded in its mating acetabular liner. C) Femoral head from the walking-only cycles test group, from the specimen having the fewest number (seven) of third body particles for that test group embedded in its mating acetabular liner; the parallel scratches likely indicate an embedded particle shifting around between load cycles.