The 2009 Frank Stinchfield Award

“Hip Squeaking”

A Biomechanical Study of Ceramic-on-ceramic Bearing Surfaces

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Abstract We designed and implemented an in vitro bench test to simulate and identify potential biomechanical causes for hip squeaking with alumina ceramic-on-ceramic bearing surfaces. All bearings were third-generation alumina ceramic with a 32-mm head coupled with a 56-mm acetabular component with a 32-mm ceramic insert. Conditions for testing were normal gait, high load, stripe wear, stripe wear in extreme load, metal transfer, edge wear with extreme load, and microfracture. Each condition was tested two times in dry conditions and two times in a lubricated condition with 25% bovine serum. Squeaking was reproduced in all dry conditions. It occurred quickly with high load, stripe wear, or metal transfer. Once squeaking occurred, it did not stop. Squeaking disappeared for all

conditions when a small amount of lubricant was introduced. In lubricated conditions, squeaking was only reproduced for the material transfer condition. Our observations suggest squeaking is a problem of ceramic-ceramic lubrication and that this noise occurs when the film fluid between two surfaces is disrupted. Material (metal) transfer was the only condition that led to squeaking in a lubricated situation.

Introduction

THA is one of the most common orthopaedic procedures performed for end-stage osteoarthritis of the hip. It provides marked durable improvement in pain and function [6]. Traditionally, metal-on-polyethylene has been established as a reliable and durable bearing surface. However, wear and wear debris associated with osteolysis remain potential complications with this bearing.

Several alternative bearings have been used in attempts to reduce wear and osteolysis. These include alternative polyethylenes, metal-on-metal bearings, ceramic-on-metal bearings, and alumina ceramic-on-ceramic bearings. Ceramic-on-ceramic was developed in the early 1970s by Pierre Boutin [4, 5]. In vitro wear rates show up to 4000 times less wear than metal-on-conventional polyethylene [7]. Ceramics are frequently used throughout the world for young, active patients. In the United States, FDA authorization for ceramic-on-ceramic bearings was approved in March 2003. Many clinic studies have proven ceramic efficacy in terms of wear and osteolysis [3, 11]. However, as a result of the rigidity and brittleness of the ceramic insert, there is a small risk of fracture. Fracture rates range from 0.005% to 0.02% for alumina bearing surfaces [10].

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More recently, a disturbing squeaking noise has been heard in some patients with ceramic-on-ceramic bearing surfaces. Squeaking incidence has been reported between 2.7% [16] and 7% [15]. Previous studies based on clinical retrieval data tried to explain the exact etiology of this phenomenon and concluded it was multifactorial or that the exact cause was still elusive [13, 16, 18, 21, 23]. Morlock et al. reported a case of mismatch of the bearing surfaces [13] and believed this was a possible cause of squeaking noise. Walter et al. concluded squeaking was dependent on patient factors, implant design factors, and surgical factors [20, 21]. Toni et al. [19] suggested the noise was an early clinical sign of liner chipping or fracture or head stripe wear.

The aim of our study was to document in vitro whether any of the following factors contributed to squeaking ceramic-on-ceramic bearing surfaces: absence of lubrication, high loads, stripe wear, edge wear, metal transfer, microcracks.

Materials and Methods

This study looked at seven different clinical situations in the laboratory (see subsequently) to see which led to hip squeaking. We mounted a conventional ceramic-on-ceramic hip bearing surface to a hip simulator to assess in vitro squeaking. The custom-made hip simulator was designed for this study (Fig. 1). The acetabular cup of the prosthesis was housed in a rotating jig, which was in turn connected to a DC motor through a bar linkage system (Figs. 1, 2). The rotation speed of the motor was adjusted by a commercially available speed controller. Because we attempted to reproduce a squeaking noise and were not studying impingement or extreme range of motion, we used unidirectional motion free of impingement. As a result, the

length of the bar linkage system was designed to allow no more than 80° of flexion/extension motion of the acetabular cup. The acetabular components were positioned in 45° of abduction (lateral opening) and 20° of anteversion. The components were locked in place with a collar of acrylic bone cement. The femoral head component was fixed to a servohydraulic biaxial testing machine (MTS, Eden Prairie, MN), which applied a prescribed amount of static compressive axial loading to the bearing surface of the prosthesis.

One type of conventional ceramic acetabular component (Horizon; Amplitude, Porte du grand Lyon, Neyron, France) and their corresponding ceramic femoral heads (Amplitude) were used for the testing conditions. Ceramics were produced by CeremTec Ag (Plochingen, Germany).

The acetabular components were 56 mm outer diameter, and the conventional ceramic acetabular liners (Amplitude) were inserted into the acetabular component. We articulated this with a 32-mm ceramic femoral head with neutral neck length. These sizes were chosen because they are commonly clinically used sizes with ceramic THA. All ceramics were alumina (ISO 6474, BioloX Forte®, third-generation hot isostatic pressed) produced by CeremTec Ag and commercialized by Amplitude. All components were produced, packaged, and sterilized according to product specifications. Different clinical situations and lubrications were applied in the testing condition. Situations that tested were termed normal gait, extreme load, stripe wear, stripe wear and extreme load, metal transfer, edge wear and extreme load, and microfracture. Each

Fig. 1 A diagram of the custom-made testing device hip simulator is shown.

Fig. 2 A photograph of the custom-made device is shown. 1 = Servohydraulic testing machine; 2 = box; 3 = rotating table; 4 = bar linkage; 5 = rotating jig; 6 = motor.

Fig. 3 A photograph of testing in dry conditions is shown.

Fig. 4 A photograph of testing in lubricated conditions is shown.

situation was tested two times in dry conditions (Fig. 3) and two times in lubricated conditions with a 25% bovine serum (Fig. 4). Each situation was tested up to 11,000 cycles to reproduce a squeaking noise. Squeaking noise was defined as a high-pitched noise audible to the human ear. Lubricant used for this test was 25% bovine newborn calf serum diluted with a solution of 0.1% sodium azide (to prevent bacterial degradation).

The following were the definitions of each of the test conditions: (1) Normal gait consisted of new implants

Fig. 5 A photograph of stripe wear produced on the ceramic head is shown.

loaded in the testing machine and physiological normal loading was applied defined as two times normal body weight of 70 kg (approximately 1370 N). The speed of rotation was approximately two cycles per second. (2) Extreme loading was performed using the same model and applying 2000 N of force on the testing machine. (3) Stripe wear (Fig. 5) is a narrow edge of damage seen on retrieved femoral heads from a ceramic-on-ceramic hip bearing couple. Stripe wear can result from multiple clinical conditions, but it is typically caused by line contact from the femoral head and the edge of the ceramic liner. Clinically, stripe wear can occur because of component malposition in which high contact stresses are seen between the femoral head and the edge of the liner [22]. Recently, it has also been proposed that microseparation of the bearing surfaces occurs during the swing phase of gait with subsequent edge loading with heel strike leading to the stripe wear [14]. In this study, stripe wear was reproduced on the ceramic bearing surface by applying extreme edge loading between the ceramic head and the ceramic cup. Stripe wear was parallel to the motion on the femoral head. It was placed on the top of the head where the forces were maximum. (4) Stripe wear and extreme loading were performed using the same stripe wear model as previously described and applying 2000 N of force on the testing machine. (5) Material transfer (Fig. 6) refers to metal that is transferred to the bearing surface. Clinically multiple situations can lead to this. Some ceramic-on-ceramic bearing surfaces have a metal rim when impingement occurs. The metal can be transferred to the bearing surface. A metal source from the trunion conflicting with the acetabular component can also lead to material transfer. In this study, material transfer

Fig. 6 A photograph of metal transfer on the ceramic head is shown.

was reproduced by striking the ceramic ball with a metal piece of titanium (Ti-6AL 4v) until visible metal transfer occurred on the femoral head. Metal transfer was placed at the same place as the stripe wear. (6) Edge wear is the result of microseparation occurring during the swing phase of gait clinically. Edge wear in this study was created on the acetabular component by striking the acetabular ceramic with a piece of ceramic femoral head approximately 10 times, and in this scenario, extreme load (2000 N) was applied. (7) Microfracture was implemented onto the ball by hitting it with a mallet, protecting the surface with a fabric material. This led to a microcrack in the ceramic bearing surface.

Before loading the ceramic, we performed the tests without any components to be sure the noise produced was not produced by the machine. No noise was produced up to 11,000 cycles confirming the machine did not make any audible noise when tested.

Results

Squeaking was easily reproduced in all dry conditions (Table 1). (Supplemental materials are available with the online version of CORR; see video #1.) For normal gait situations without lubrication, squeaking occurred after 2400 cycles. The squeaking noise was constant and did not disappear with time. It remained constant with modified frequency (one cycle/second or less). When examining the cup and femoral head after testing, we found little visible evidence of stripe wear or of any physical damage in the bearing surface. Under high load, another test was performed with a new bearing surface. Squeaking occurred after 300 cycles. Again, it did not disappear and remained constant. Stripe wear with normal loading, stripe wear with extreme loading, material transfer with normal loading, and edge wear with normal loading squeaking occurred immediately and remained constant. For the microfracture in a dry condition, squeaking occurred after 4000 cycles and remained constant. In all of these dry conditions, when a small amount of lubricant was continually added to the test condition, squeaking would disappear. Once the

Table 1. Situations without lubrication

Conditions	Squeaking	Number of cycles for squeaking
Normal gait	✓	2400
Normal gait (repeated same components)	✓	300
High load	✓	300
Stripe wear	✓	Immediately
Stripe wear and high load	✓	Immediately
Material transfer	✓	Immediately
Edge wear	✓	Immediately
Microfractures	✓	4000

Table 2. Situation with lubrication

Conditions	Squeaking	Number of cycles for squeaking
Normal gait	0	
Normal gait (repeated same components)	0	
High load	0	
Stripe wear	0	
Stripe wear and high load	0	
Material transfer	✓	Immediately; disappear after 30 cycles
Edge wear	0	
Microfractures	0	

lubricant was stopped, the squeaking would reappear and remain constant.

For the lubricated conditions (Table 2), squeaking occurred only for the material transfer situation. For all other situations (normal gait, high load, microfracture, stripe wear, and edge wear), we were not able to reproduce squeaking even after more than 11,000 cycles. For the material transfer situation, squeaking occurred immediately.

Discussion

Ceramic-on-ceramic (COC) is a commonly used bearing surface for THA in young, active adults. It has been used since the 1970s in Europe [8, 9]. Thanks to the new generation of alumina COC bearing, risk of fracture has been dramatically reduced from approximately one in 2000 to one in 10,000 implants [2, 17, 22]. Short-term clinical results with this third generation are favorable [2, 24]. Noise can occur after any hip arthroplasty, including metal-on-metal [1] and COC during in vitro testing [16]. The aim

of our study was to identify potential in vitro contributing factors to squeaking COC bearing surfaces.

Our study has some limitations. First, we only tested unidirectional hip motion without microseparation. Second, we did not examine impingement or extreme motion. Third, we did not use an actual femoral stem of a total hip. Despite these limitations, we believe this well-controlled testing situation simulated multiple “real-life” situations.

In our in vitro study, squeaking occurs in all nonlubricated conditions. In those conditions, it remains stable and constant, even when modifying the cycle speed. Comparatively, in lubricated conditions, such noise only occurs when metal particles are interposed between the head and the liner. For all the other lubricated conditions, we were not able to reproduce squeaking, even after more than 11,000 cycles. Moreover, in a dry condition with the addition of a small amount of lubricant, squeaking noise was immediately interrupted. This suggests the exact etiology of squeaking is a disruption of fluid lubrication. This disruption seems to be caused by the interposition of particles (third body) between the head and the cup, particularly by metal particles. We believe such results are in accordance with clinical findings.

In his clinical study, Respeto et al. found metal particles and stripe wear on the ceramic head of the four prostheses they revised with a problem of squeaking noise [16]. Moreover, Walter et al. [20, 21] found bands of stripe wear in many ceramic heads revised that did not have any problem of squeaking. This is consistent with why stripe wear is not the most important phenomenon for producing the noise, but the transfer of metal particles appears more important.

Nevertheless, Taylor et al. reproduced in vitro phenomena squeaking with the presence of stripe wear on the ceramic head [18]. In our study, we found squeaking appeared immediately in the nonlubricated conditions with the presence of stripe wear (with or without extreme load) more quickly than for the standard gait conditions, but we were not able to reproduce squeaking with stripe wear on lubricated conditions. This suggests stripe wear can accelerate the phenomenon of squeaking, like edge wear, microfractures, and extreme load, but is not the major cause of the production of it. Indeed, in the lubricated conditions, the only way to reproduce squeaking was the presence of metal particles as a third body.

Keurentjes et al. [12] suggested a short femoral neck was a risk factor for squeaking. This is consistent with our findings. A short neck potentially has a higher risk of impingement, which can cause easier transfer of metal particles to the bearing surface. Similarly, squeaking seems more frequently reported with some designs of prostheses. Respeto et al. [16] reported squeaking only occurred with one design acetabular component (one with a metal rim around the edge).

As a result of these findings and our in vitro results, we suggest squeaking noise in COC bearings is a problem of COC lubrication. This phenomenon occurs when the film fluid between the two surfaces in contact is disrupted. We believe this interruption is most commonly the result of metal particle transfer as a third body between COC. Metal transfer as the primary mode leading to fluid lubrication disruption may explain why squeaking is more common in certain designs of prostheses.

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