Review Article

Hip Squeaking after Ceramic-on-ceramic Total Hip Arthroplasty

Guo-Liang Wu, Wei Zhu, Yan Zhao, Qi Ma, Xi-Sheng Weng

Department of Orthopaedic Surgery, Peking Union Medical College Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing 100730, China

Abstract

Objective: The present study aimed to review the characteristics and influencing factors of squeaking after ceramic-on-ceramic (CoC) total hip arthroplasty (THA) and to analyze the possible mechanisms of the audible noise.

Data Sources: The data analyzed in this review were based on articles from PubMed and Web of Science.

Study Selection: The articles selected for review were original articles and reviews found based on the following search terms: "total hip arthroplasty", "ceramic-on-ceramic", "hip squeaking", and "hip noise."

Results: The mechanism of the squeaking remains unknown. The possible explanations included stripe wear, edge loading, a third body, fracture of the ceramic liner, and resonance of the prosthesis components. Squeaking occurrence is influenced by patient, surgical, and implant factors.

Conclusions: Most studies indicated that squeaking after CoC THA was the consequence of increasing wear or impingement, caused by prosthesis design, patient characteristics, or surgical factors. However, as conflicts exist among different articles, the major reasons for the squeaking remain to be identified.

Key words: Ceramic-on-ceramic; Squeaking; Total Hip Arthroplasty

Introduction

Total hip arthroplasty (THA) is an effective therapeutic method for advanced hip diseases that can restore the physical function of the hip joint and improve the quality of life in most patients. Common materials used for THA include metal, polyethylene, and bioceramics. Combinations include metal-on-metal, metal-on-polyethylene, ceramic-on-plastic, and ceramic-on-ceramic (CoC).[1] With stable chemical inertia, reliable biocompatibility, high hardness, and a low coefficient of friction, CoC total hip implants have been popularized in recent years.[2,3]

CoC bearing for THA was first introduced by Boutin in France during the 1970s.[4] With the application of third- and fourth-generation ceramic total hip bearing surfaces, CoC implants are currently widely utilized in THA.

However, even with the application of new ceramic surface materials, various clinical problems still exist with CoC hip prostheses. One such problem is postsurgery squeaking, which affects patients' quality of life. Recent research has shown that the incidence of noise emanating from CoC-bearing THAs is nearly three times more frequent than the noise that emanates from ceramic-on-polyethylene hip implants.[5] Nevertheless, explanations for hip squeaking are still limited.

Characteristics of Squeaking

There is neither a specific definition for postsurgery squeaking nor a universal categorization for the sound. Kuo *et al.*[6] studied 125 patients who had undergone THA, eight of whom reported squeaking noises, including clicking, grinding, and

Access this article online

Quick Response Code:

Website: www.cmj.org

DOI: 10.4103/0366-6999.186654

Address for correspondence: Dr. Xi-Sheng Weng, Department of Orthopaedic Surgery, Peking Union Medical College Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing 100730, China
E-Mail: xshweng@medmail.com.cn

Received: 12-04-2016 **Edited by:** Qiang Shi

How to cite this article: Wu GL, Zhu W, Zhao Y, Ma Q, Weng XS. Hip Squeaking after Ceramic-on-ceramic Total Hip Arthroplasty. Chin Med J 2016;129:1861-6.

snapping. Jarret *et al*.[7] described the sound as clicking, popping, clunking, and grinding. In terms of sound analysis, the noise is composed of a series of sounds with individual frequencies, with a fundamental frequency between 400 and 7500 Hz.[8] Further studies have demonstrated that the fundamental frequency is approximately 1500 Hz in male patients and 2500 Hz in females.[9]

It should be noted that squeaking is not usually associated with abnormal feelings or functional impairment.[10-14] In addition, there has been no significant difference in satisfaction between patients with squeaking and silent hips.[15]

Occurrences of Squeaking

Reported occurrences of squeaking vary among different studies [Table 1]; the prevalence was reported to be around 0.5% by Walter *et al*.[8] but 10.6% by Cogan *et al*.[22] Another study showed that the prevalence could reach up to 24.6%.[29] Such variation could be ascribed not only to the difference in sample sizes among the studies but also to inevitable subjective bias due to a lack of unified scales for noise assessment. Owen *et al*.[30] summarized studies of squeaking after THA over recent years where 545 of 15,131 cases reported squeaking, with an average incidence of 4.2%. In these studies, the incidence rate was 1.2% in self-reported studies, but as high as 4.5% in scale-based ones, which is convincing evidence for the existence of subjective bias.

The onset of squeaking was usually 14–40 months after THA surgery.[10,11,15,17,29] Although there was barely any evidence indicating a relationship between squeaking and osteolysis, heterotopic ossification, and other postsurgery biomechanical problems, such as instability and functional limitations,[11,13,14,32-36] it can affect patients' quality of life[20,21,37] and in some cases, lead to revision surgery. In different studies of patients who had received CoC THA, the incidence of revision surgery for post-THA squeaking ranged between 0 and 4.7%.[17] The estimated prevalence for revision based on a meta-analysis was approximately 0.2%.[30] However, the real proportion could be far higher, taking into account both patients on the waiting list or those about to undergo the second operation.

Table 1: Studies reported occurrence of squeaking associated with CoC THA

Authors	Year	Hip joints (*n*)	Squeaking (%)
Walter *et al*.[8]	2008	2397	0.5
Restrepo *et al*.[12]	2008	1056	2.8
Capello *et al*.[16]	2008	380	0.8
Keurentjes *et al*.[17]	2008	43	20.9
Jarrett *et al*.[7]	2009	149	10.7
Boyer *et al*.[18]	2010	76	1.3
Choi *et al*.[19]	2010	173	4.6
Mai *et al*.[20]	2010	320	17.2
Sexton *et al*.[15]	2011	2406	3.1
Schroder *et al*.[21]	2011	375	2.4
Cogan *et al*.[22]	2011	265	10.6
Parvizi *et al*.[23]	2011	1745	5.6
Nikolaou *et al*.[24]	2012	34	8.8
Haq *et al*.[25]	2012	1002	1.5
Chevillotte *et al*.[26]	2012	89	5.6
McDonnell *et al*.[27]	2013	208	20.7
Kiyama *et al*.[28]	2013	183	12.0
Owen *et al*.[29]	2014	69	24.6
Owen *et al*.[30]	2014	16,828	4.2
Aoude *et al*.[31]	2015	140	0.7

CoC: Ceramic-on-ceramic; THA: Total hip arthroplasty.

Risk Factors of Squeaking

Various factors have been proven to be relevant to post-THA squeaking and can be divided into three categories: patient, surgical, and implant factors.[10]

Patient factors

A retrospective study by Mai *et al*.[20] showed that patients who experienced squeaking were taller on average than that of patients who had not. Sexton *et al*.[15] reported that the tendency for squeaking to occur was higher in younger, heavier, and taller patients. However, a retrospective meta-analysis by Stanat and Capozzi[38] demonstrated that squeaking was solely based on body mass index (BMI); patients with a higher BMI were at a higher risk for squeaking while no significant relevance was found between squeaking and patients age, gender, height, weight, or procedural laterality.

In addition, limb length shortening and rheumatoid arthritis were also common factors for hip noise,[11,25] and patients with squeaking hips experienced more physical activities with a significantly wider range of hip joint movement, especially in terms of internal and external rotation range.[15]

Surgical factors

Implant position and orientation can play a key role in causing hip squeaking. Walter *et al*.[10] proved that high or low anteversion and inclination of the acetabular component were associated with squeaking. In patients without squeaking, 94% of the implants were installed with 25° ± 10° anteversion and 45° ± 10° inclination while only 35% of squeaking hips were within this range. Neck-socket impingement and edge loading caused by an improper component position were possible explanations for the relationship between acetabular component orientation and squeaking.[39] In addition, increased cup anteversion and inclination were found to be associated with anterior edge loading while insufficient anteversion and inclination were associated with posterior edge loading.[10,40] Moreover, reduced hip center medialization and high prosthetic femoral offset were also associated with hip squeaking.[15,28] Thus, placement of the implants during operation may directly influence the chance of squeaking.

Implant factors

The prosthesis design and the materials used are also thought to be contributing factors for squeaking. A study conducted by Parvizi *et al*.[23] reported squeaking in 92 of 1507 enrolled patients (6%), all of whom had received implants with an elevated rim. The noise could be either a consequence of rim impingement when the lubricating layer was compromised by fallen fragments into the space between friction pairs or a direct effect of friction at the impingement site. In addition, the impingement also increased the chance of mismatch and edge loading, resulting in further damage of the bearing surfaces.[12,32,41,42]

Some reports mentioned that specific hip joint prosthesis pairs could lead to more frequent squeaking. Stryker Trident acetabular cups paired with Stryker Accolade femoral stems showed a dramatically higher average incidence of squeaking, i.e., up to 35.6% compared with non-Stryker designs in which the incidence was only 3.6%.[11] This higher incidence is possibly due to the unique design of the Stryker system, which features a high rim and short femoral neck.

The incidence of squeaking was also reported to be related to the materials of the femoral stem but not its design. The prevalence was seven times higher for patients who had received titanium-molybdenum-zirconium-iron alloy stems (18.4%) than for those who had received titanium-aluminum-vanadium alloy ones (2.6%).[43] This phenomenon implies that the specific composition of the material and structure could influence the stiffness and fundamental frequency of the prosthesis, which has a greater tendency to induce resonance during hip joint movements, thus resulting in audible squeaking.[28,44]

It should be noted that a meta-analysis conducted by Lee *et al.*,[45] which included 132 recent studies on squeaking, showed that among numerous factors, the only significant one was the abduction angle, which was positively related to squeaking incidence. A significant difference existed among results of published studies and potential factors related to hip squeaking in the available literature are listed in Table 2.

Mechanisms of Posttotal Hip Arthroplasty Squeaking

Audible noises generated by irregular vibrations were a coeffect of impulse and amplification system.[49] Proposed mechanisms of squeaking in CoC THA are shown in Figure 1. Most studies so far have implied that post-THA squeaking is the result of disruption of the lubrication between bearing surfaces[37,43,50,51] and it could disappear when lubricants are introduced,[52] indicating that the squeaking was caused by friction. Therefore, the impulse is mainly abnormal friction force. Most studies so far have focused on factors that would modify the nature of friction pairs, thus generating abnormal friction, while some recent studies have turned to the amplification system, that is, the resonance of the implants.

Mechanisms of impulse

As mentioned above, hip squeaking will not occur under normal lubricating conditions. However, the fluid film lubrication can be disrupted by increased surface roughness (stripe wear), abnormal behaviors in the hip prosthesis (edge loading and microseparation), particulate debris between bearing surfaces (a third body), and direct destruction of implants (fracture), thus leading to direct contact of the prosthesis' bearing surfaces and the generation of noise when relative movement occurs.

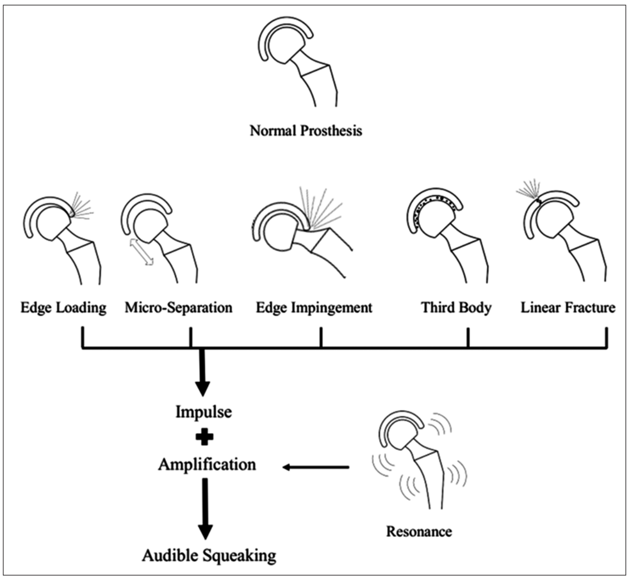

Figure 1: Proposed mechanisms of squeaking in CoC THA. CoC: Ceramic-on-ceramic; THA: Total hip arthroplasty.

Stripe wear

Stripe wear, mostly crescent-shaped, could frequently be observed during revision for THA squeaking. The wear rate of the ceramic surface increased significantly in this area. It was reported that the median wear rate of the combined implant (femoral heads and acetabular components) of noisy CoC bearings with stripe wear was 6.7 mm^3/year compared to a median of 0.14 mm^3/year in the silent control group, representing a 45-fold increase.[53] The prevalence of squeaking clearly increased with the occurrence of stripe wear.[54] Given the fact that hip squeaking mostly occurs several months after surgery[55] and that the formation of stripe wear also requires some time to develop, the relationship between squeaking and stripe wear may well be speculative.

Edge loading

Because of the process and technology of implant production, the ceramic liner was not a continuous smooth surface, but rather one with hard edges at the margin of the bearing surface that sat a couple of millimeters recessed from the face of the implant.[49] The friction pairs were uniformly forced when the femoral head moved normally inside the liner. However, under certain circumstances, the contact point between the femoral head and the liner would move over the hard edge, leading to an increase in stress (referred to as edge loading), hence causing stripe wear.

Some researchers suspected that edge loading might be related to impingement between the femoral neck and

Table 2: Studies demonstrating risk factors associated with CoC THA squeaking

Authors	Relevant factors	Irrelevant factors
Mai *et al*.[20]	Height, neck geometry, V40 neck/Trident combination and C-taper/Trident combination	Age, gender, weight, BMI, indication, head size, acetabular component
Sexton *et al*.[15]	Height, weight, age, femoral offset, inclination, anteversion, medialization	Femoral head size, BMI
Stanat and Capozzi[38]	BMI	Age, gender, height, weight, procedural laterality
Walter *et al*.[10]	Height, weight, age, anteversion, inclination, impingement, edge loading	
Eickmann *et al*.[39]	Neck-socket impingement	
Kiyama *et al*.[28]	Age, obesity, cup lateralization, Accolade stem, shortened head length, activity level	Loosening of prosthesis
Parvizi *et al*.[23]	Neck impingement, Trident acetabular cup	
Restrepo *et al*.[12]	Edge loading, stripe wear, the kinematics of the hip implant	Acetabular component positioning, intervention, abduction, femoral head size, type of femoral stem, impingement, age, height
Rodríguez *et al*.[41]	Rim impingement, lubrication disruption, Trident cup with Accolade stem	
Yang *et al*.[32]	Elevated titanium rim	
Swanson *et al*.[11]	Combination of Stryker Trident cup and Accolade stem, short femoral neck length, rheumatoid arthritis	Age, sex, height, activity level, acetabular component size, femoral head size, BMI, laterality, femoral offset
Restrepo *et al*.[43]	Accolade stem	Age, height, weight, BMI, abduction, anteversion
Restrepo *et al*.[44]	Type of motion activity	Pain
Lee *et al*.[45]	Abduction angle	Age, gender, BMI, anteversion, head size, type of femoral stem and acetabular cup
McDonnell *et al*.[27]	Range of motion, inclination, anteversion, head size, ligament laxity	Age, height, weight, BMI, gender, stem type
Chevillotte *et al*.[46]	Trident acetabular cup, anteversion	Age, gender, height, weight
Haq *et al*.[25]	BMI, acetabular opening angle, limb length shortening	Age, acetabular anteversion
Hothan *et al*.[47]	Stem design, assembled stem, axial load	Cup design, bearing clearance
Bernasek *et al*.[48]	Gender, inclination	
Choi *et al*.[19]	Head size, gender	Age, height, weight, BMI, cup size, neck length, abduction

CoC: Ceramic-on-ceramic; THA: Total hip arthroplasty; BMI: Body mass index.

acetabular cup. Restrepo *et al*.[12] studied five patients (with six THA hip joints) who had undergone revision surgery for squeaking, posteroinferior neck-rim impingement, as evidenced by indentation in the rim, was observed in four of these acetabular components. The prevalence of impingement was 7 of 12 according to Walter *et al*.[53] The impingement would lead to dislocation of the femoral head, which could result in an altered distribution of surface stress and consequent edge loading. It should be noted, though, that not all stripe wear cases demonstrated edge impingement.

Microseparation was one of the hypotheses for edge loading.[56] Separation between bearing surfaces during swinging of the artificial hip joint could lead to edge loading when the patient's leg touches the ground. One experiment *in vivo* proved the existence of microseparation,[57] which could be a consequence of lowered joint stability due to post-THA reduction of soft tissues, such as articular capsules, ligaments, and muscles. However, some researchers have argued that edge loading would not take place with normal walking, but rather only where the hip is flexed, such as when the patient is rising from a chair or climbing a high step.[40]

Third body

Friction force, except for the contact force, is also modified by the friction coefficient. Alternation of the lubrication fluid status could directly lead to a change of the friction coefficient, and increasing the friction coefficient could ultimately result in unstable vibration and an audible noise. It was reported that impingement between the femoral neck and acetabular cup could presumably be caused by malposition, or that improper design of the implants could produce third bodies.[11,39] Metal debris from impingement could fall inside the bearing surface and disrupt the lubrication film, which would bring about an increased wear rate of the ceramic surfaces, thus producing ceramic debris. Third bodies composed of both metal and ceramic debris further facilitate abrasion of the joint bearing surfaces. Chemical identification with microanalysis proved the presence of ceramic particles in the synovial fluid of squeaking hips.[58] Experiments *in vitro* also indicated that the friction coefficient could be dozens of times higher than normal situations with the existence of a third body as well as of edge loading,[59] implying a relationship between third bodies and abnormal friction.

Fractures of ceramic liner

Along with wearing, fractures of the ceramic liner could also lead to modified nature of friction surfaces. Abdel reported four cases with audible hip squeaking,[60] all with fractured ceramic liners. It was remarkable that all these patients also had complaints of sharp pain.

Amplification system - resonance

Most current studies of THA squeaking have focused on mechanisms of impulse while investigations were limited to the amplification system or resonance factors. Considering the composition of ceramic hip prostheses, the components responsible for resonance could be either one single part (metal cup, ceramic liner, ceramic femoral head, and femoral stem) or combinations of parts, such as acetabular components (pelvic bone, metal cup, and ceramic liner) or femoral components (ceramic head, metal stem, and femur).

Resonance does not occur unless the vibration frequency approximates the natural frequency of vibration components. It was reported that frequency of squeaking was between 400 and 7500 Hz,[8] which indicated that the natural frequency of components contributing to audible squeaking should be within this range. For single parts, experiments reported that both femoral stem and metal cup were eligible.[8,61,62] However, when it comes to combined components, only the natural frequency of femoral components (head + stem + femur) was within this range. A finite element model of pelvis + stem + femur showed that the bending and torsion of the femoral component at lower frequencies may be the source of unstable vibrations for squeaking.[61]

With the fact that both femoral components and acetabular components are fixed combinations, it seems plausible to conduct an analysis of combination frequency. However, the stiffness of individual parts in combined components is not identical and the metal cup might be deformed with edge loading; hence, the shell-liner taper system could be uncoupled as reported by Walter *et al*.[8] Therefore, the ceramic liner could tilt out of the metal acetabular shell where the analysis of combination frequency becomes inapplicable.

Conclusions

So far, most published evidence indicates that squeaking after CoC THA is the consequence of increasing wear or impingement related to prosthesis design, patient, and surgical factors, which influence the frictional driving force and dynamic response. However, the major reasons for squeaking remain to be identified as conflicts still exist among certain studies. Future research should focus on investigations of *in vivo* conditions, reasonable methods of *in vitro* stimulations, and follow-up tactics and scales, which are critical for improving reproducibility among individual studies.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Askari E, Flores P, Dabirrahmani D, Appleyard R. A review of squeaking in ceramic total hip prostheses. Tribol Int 2016;93:239-56. doi: 10.1016/j.triboint.2015.09.019.
2. Manley MT, Sutton K. Bearings of the future for total hip arthroplasty. J Arthroplasty 2008;23 7 Suppl:47-50. doi: 10.1016/j.arth.2008.06.008.
3. Fisher J, Jin Z, Tipper J, Stone M, Ingham E. Tribology of alternative bearings. Clin Orthop Relat Res 2006;453:25-34. doi: 10.1097/01.blo.0000238871.07604.49.
4. Boutin P. Total arthroplasty of the hip by fritted alumina prosthesis. Experimental study and 1st clinical applications. Orthop Traumatol Surg Res 2014;100:15-21. doi:10.1016/j.otsr.2013.12.004.
5. Wyatt MC, Jesani S, Frampton C, Devane P, Horne JG. Noise from total hip replacements: A case-controlled study. Bone Joint Res 2014;3:183-6. doi: 10.1302/2046-3758.36.2000274.
6. Kuo FC, Liu HC, Chen WS, Wang JW. Ceramic-on-ceramic total hip arthroplasty: Incidence and risk factors of bearing surface-related noises in 125 patients. Orthopedics 2012;35:e1581-5. doi: 10.3928/01477447-20121023-12.
7. Jarrett CA, Ranawat AS, Bruzzone M, Blum YC, Rodriguez JA, Ranawat CS. The squeaking hip: A phenomenon of ceramic-on-ceramic total hip arthroplasty. J Bone Joint Surg Am 2009;91:1344-9. doi: 10.2106/JBJS.F.00970.
8. Walter WL, Waters TS, Gillies M, Donohoo S, Kurtz SM, Ranawat AS, *et al.* Squeaking hips. J Bone Joint Surg Am 2008;90 Suppl 4:102-11. doi: 10.2106/JBJS.H.00867.
9. Currier JH, Anderson DE, Van Citters DW. A proposed mechanism for squeaking of ceramic-on-ceramic hips. Wear 2010;269:782-9. doi: 10.1016/j.wear.2010.08.006.
10. Walter WL, O'toole GC, Walter WK, Ellis A, Zicat BA. Squeaking in ceramic-on-ceramic hips: The importance of acetabular component orientation. J Arthroplasty 2007;22:496-503. doi: 10.1016/j.arth.2006.06.018.
11. Swanson TV, Peterson DJ, Seethala R, Bliss RL, Spellmon CA. Influence of prosthetic design on squeaking after ceramic-on-ceramic total hip arthroplasty. J Arthroplasty 2010;25 6 Suppl:36-42. doi: 10.1016/j.arth.2010.04.032.
12. Restrepo C, Parvizi J, Kurtz SM, Sharkey PF, Hozack WJ, Rothman RH. The noisy ceramic hip: Is component malpositioning the cause? J Arthroplasty 2008;23:643-9. doi: 10.1016/j.arth.2008.04.001.
13. Murphy SB, Ecker TM, Tannast M. Incidence of squeaking after alumina ceramic-ceramic total hip arthroplasty. J Arthroplasty 2008;23:327. doi: 10.1016/j.arth.2008.01.284.
14. Baek SH, Kim SY. Cementless total hip arthroplasty with alumina bearings in patients younger than fifty with femoral head osteonecrosis. J Bone Joint Surg Am 2008;90:1314-20. doi: 10.2106/Jbjs.G.00755.
15. Sexton SA, Yeung E, Jackson MP, Rajaratnam S, Martell JM, Walter WL, *et al.* The role of patient factors and implant position in squeaking of ceramic-on-ceramic total hip replacements. J Bone Joint Surg Br 2011;93:439-42. doi: 10.1302/0301-620X.93B4.25707.
16. Capello WN, D'Antonio JA, Feinberg JR, Manley MT, Naughton M. Ceramic-on-ceramic total hip arthroplasty: Update. J Arthroplasty 2008;23 7 Suppl:39-43. doi: 10.1016/j.arth.2008.06.003.
17. Keurentjes JC, Kuipers RM, Wever DJ, Schreurs BW. High incidence of squeaking in THAs with alumina ceramic-on-ceramic bearings. Clin Orthop Relat Res 2008;466:1438-43. doi: 10.1007/s11999-008-0177-8.
18. Boyer P, Huten D, Loriaut P, Lestrat V, Jeanrot C, Massin P. Is alumina-on-alumina ceramic bearings total hip replacement the right choice in patients younger than 50 years of age? A 7- to 15-year follow-up study. Orthop Traumatol Surg Res 2010;96:616-22. doi: 10.1016/j.otsr.2010.02.013.
19. Choi IY, Kim YS, Hwang KT, Kim YH. Incidence and factors associated with squeaking in alumina-on-alumina THA. Clin Orthop Relat Res 2010;468:3234-9. doi: 10.1007/s11999-010-1394-5.
20. Mai K, Verioti C, Ezzet KA, Copp SN, Walker RH, Colwell CW Jr. Incidence of 'squeaking' after ceramic-on-ceramic total hip arthroplasty. Clin Orthop Relat Res 2010;468:413-7. doi: 10.1007/s11999-009-1083-4.
21. Schroder D, Bornstein L, Bostrom MP, Nestor BJ, Padgett DE, Westrich GH. Ceramic-on-ceramic total hip arthroplasty: Incidence of instability and noise. Clin Orthop Relat Res 2011;469:437-42. doi: 10.1007/s11999-010-1574-3.
22. Cogan A, Nizard R, Sedel L. Occurrence of noise in alumina-on-alumina total hip arthroplasty. A survey on 284

consecutive hips. Orthop Traumatol Surg Res 2011;97:206-10. doi: 10.1016/j.otsr.2010.11.008.
23. Parvizi J, Adeli B, Wong JC, Restrepo C, Rothman RH. A squeaky reputation: The problem may be design-dependent. Clin Orthop Relat Res 2011;469:1598-605. doi: 10.1007/s11999-011-1777-2.
24. Nikolaou VS, Edwards MR, Bogoch E, Schemitsch EH, Waddell JP. A prospective randomised controlled trial comparing three alternative bearing surfaces in primary total hip replacement. J Bone Joint Surg Br 2012;94:459-65. doi: 10.1302/0301-620X.94B4.27735.
25. Haq RU, Park KS, Seon JK, Yoon TR. Squeaking after third-generation ceramic-on-ceramic total hip arthroplasty. J Arthroplasty 2012;27:909-15. doi: 10.1016/j.arth.2011.10.001.
26. Chevillotte C, Pibarot V, Carret JP, Bejui-Hugues J, Guyen O. Hip squeaking: A 10-year follow-up study. J Arthroplasty 2012;27:1008-13. doi: 10.1016/j.arth.2011.11.024.
27. McDonnell SM, Boyce G, Baré J, Young D, Shimmin AJ. The incidence of noise generation arising from the large-diameter delta motion ceramic total hip bearing. Bone Joint J 2013;95-B:160-5. doi: 10.1302/0301-620X.95B2.30450.
28. Kiyama T, Kinsey TL, Mahoney OM. Can squeaking with ceramic-on-ceramic hip articulations in total hip arthroplasty be avoided? J Arthroplasty 2013;28:1015-20. doi: 10.1016/j.arth.2012.10.014.
29. Owen D, Russell N, Chia A, Thomas M. The natural history of ceramic-on-ceramic prosthetic hip squeak and its impact on patients. Eur J Orthop Surg Traumatol 2014;24:57-61. doi: 10.1007/s00590-012-1142-5.
30. Owen DH, Russell NC, Smith PN, Walter WL. An estimation of the incidence of squeaking and revision surgery for squeaking in ceramic-on-ceramic total hip replacement: A meta-analysis and report from the Australian Orthopaedic Association National Joint Registry. Bone Joint J 2014;96-B:181-7. doi: 10.1302/0301-620X.96B2.32784.
31. Aoude AA, Antoniou J, Epure LM, Huk OL, Zukor DJ, Tanzer M. Midterm outcomes of the recently FDA approved ceramic on ceramic bearing in total hip arthroplasty patients under 65 years of age. J Arthroplasty 2015;30:1388-92. doi: 10.1016/j.arth.2015.03.028.
32. Yang CC, Kim RH, Dennis DA. The squeaking hip: A cause for concern-disagrees. Orthopedics 2007;30:739-42.
33. Gallo J, Goodman SB, Lostak J, Janout M. Advantages and disadvantages of ceramic on ceramic total hip arthroplasty: A review. Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub 2012;156:204-12. doi: 10.5507/bp. 2012.063.
34. Tateiwa T, Clarke IC, Williams PA, Garino J, Manaka M, Shishido T, *et al.* Ceramic total hip arthroplasty in the United States: Safety and risk issues revisited. Am J Orthop (Belle Mead NJ) 2008;37:E26-31.
35. D'Antonio JA, Sutton K. Ceramic materials as bearing surfaces for total hip arthroplasty. J Am Acad Orthop Surg 2009;17:63-8. doi: 10.5435/00124635-200902000-00002.
36. Ecker TM, Robbins C, van Flandern G, Patch D, Steppacher SD, Bierbaum B, *et al.* Squeaking in total hip replacement: No cause for concern. Orthopedics 2008;31:875-6, 884. doi: 10.3928/01477447-20080901-11.
37. Ranawat AS, Ranawat CS. The squeaking hip: A cause for concern-agrees. Orthopedics 2007;30:738, 743.
38. Stanat SJ, Capozzi JD. Squeaking in third- and fourth-generation ceramic-on-ceramic total hip arthroplasty: Meta-analysis and systematic review. J Arthroplasty 2012;27:445-53. doi: 10.1016/j.arth.2011.04.031.
39. Eickmann T, Manaka M, Clarke IC, Gustafson A, editors. Squeaking and neck-socket impingement in a ceramic total hip arthroplasty. Key Engineering Materials 2002;240:849-52. doi: 10.4028/ www.scientific.net/ KEM.240-242.849.
40. Walter WL, Insley GM, Walter WK, Tuke MA. Edge loading in third generation alumina ceramic-on-ceramic bearings: Stripe wear. J Arthroplasty 2004;19:402-13. doi: 10.1016/j.arth.2003.09.018.
41. Rodríguez JA, Gonzalez DelaValle A, McCook N. Squeaking in total hip replacement: A cause for concern. Orthopedics 2008;31:874, 877-8. doi: 10.3928/01477447-20080901-29.
42. Barrack RL, Burak C, Skinner HB. Concerns about ceramics in THA. Clin Orthop Relat Res 2004;429:73-9. doi: 10.1097/01.blo.0000150132.11142.d2.
43. Restrepo C, Post ZD, Kai B, Hozack WJ. The effect of stem design on the prevalence of squeaking following ceramic-on-ceramic bearing total hip arthroplasty. J Bone Joint Surg Am 2010;92:550-7. doi: 10.2106/JBJS.H.01326.
44. Restrepo C, Matar WY, Parvizi J, Rothman RH, Hozack WJ. Natural history of squeaking after total hip arthroplasty. Clin Orthop Relat Res 2010;468:2340-5. doi: 10.1007/s11999-009-1223-x.
45. Lee TH, Moon YW, Lim SJ, Park YS. Meta-analysis of the incidence and risk factors for squeaking after primary ceramic-on-ceramic total hip arthroplasty in Asian patients. Hip Pelvis 2014;26:92. doi: 10.5371/hp.2014.26.2.92.
46. Chevillotte C, Trousdale RT, An KN, Padgett D, Wright T. Retrieval analysis of squeaking ceramic implants: Are there related specific features? Orthop Traumatol Surg Res 2012;98:281-7. doi: 10.1016/j.otsr.2011.12.003.
47. Hothan A, Huber G, Weiss C, Hoffmann N, Morlock M. The influence of component design, bearing clearance and axial load on the squeaking characteristics of ceramic hip articulations. J Biomech 2011;44:837-41. doi: 10.1016/j.jbiomech.2010.12.012.
48. Bernasek T, Fisher D, Dalury D, Levering M, Dimitris K. Is metal-on-metal squeaking related to acetabular angle of inclination? Clin Orthop Relat Res 2011;469:2577-82. doi: 10.1007/s11999-011-1900-4.
49. Jeffers JR, Walter WL. Ceramic-on-ceramic bearings in hip arthroplasty: State of the art and the future. J Bone Joint Surg Br 2012;94:735-45. doi: 10.1302/0301-620X.94B6.28801.
50. Laurent MP, Pourzal R, Fischer A, Bertin KC, Jacobs JJ, Wimmer MA. *In vivo* wear of a squeaky alumina-on-alumina hip prosthesis: A case report. J Bone Joint Surg Am 2011;93:e27. doi: 10.2106/JBJS.I.00930.
51. Brockett CL, Williams S, Jin Z, Isaac GH, Fisher J. Squeaking hip arthroplasties: A tribological phenomenon. J Arthroplasty 2013;28:90-7. doi: 10.1016/j.arth.2012.01.023.
52. Chevillotte C, Trousdale RT, Chen Q, Guyen O, An KN. The 2009 Frank Stinchfield Award: "Hip squeaking": A biomechanical study of ceramic-on-ceramic bearing surfaces. Clin Orthop Relat Res 2010;468:345-50. doi: 10.1007/s11999-009-0911-x.
53. Walter WL, Kurtz SM, Esposito C, Hozack W, Holley KG, Garino JP, *et al.* Retrieval analysis of squeaking alumina ceramic-on-ceramic bearings. J Bone Joint Surg Br 2011;93:1597-601. doi: 10.1302/0301-620X.93B12.27529.
54. Taylor S, Manley MT, Sutton K. The role of stripe wear in causing acoustic emissions from alumina ceramic-on-ceramic bearings. J Arthroplasty 2007;22 7 Suppl 3:47-51. doi: 10.1016/j.arth.2007.05.038.
55. Walter WL, Yeung E, Esposito C. A review of squeaking hips. J Am Acad Orthop Surg 2010;18:319-26. doi: 10.5435/00124635-201006000-00004.
56. Nevelos J, Ingham E, Doyle C, Streicher R, Nevelos A, Walter W, *et al.* Microseparation of the centers of alumina-alumina artificial hip joints during simulator testing produces clinically relevant wear rates and patterns. J Arthroplasty 2000;15:793-5. doi: 10.1054/arth.2000.8100.
57. Dennis DA, Komistek RD, Northcut EJ, Ochoa JA, Ritchie A. "*In vivo*" determination of hip joint separation and the forces generated due to impact loading conditions. J Biomech 2001;34:623-9. doi: 10.1016/S0021-9290(00)00239-6.
58. Stea S, Traina F, Beraudi A, Montesi M, Bordini B, Squarzoni S, *et al.* Synovial fluid microanalysis allows early diagnosis of ceramic hip prosthesis damage. J Orthop Res 2012;30:1312-20. doi: 10.1002/jor.22077.
59. Sariali E, Stewart T, Jin Z, Fisher J. *In vitro* investigation of friction under edge-loading conditions for ceramic-on-ceramic total hip prosthesis. J Orthop Res 2010;28:979-85. doi: 10.1002/jor.21100.
60. Abdel MP, Heyse TJ, Elpers ME, Mayman DJ, Su EP, Pellicci PM, *et al.* Ceramic liner fractures presenting as squeaking after primary total hip arthroplasty. J Bone Joint Surg Am 2014;96:27-31. doi: 10.2106/JBJS.M.00737.
61. Hua ZK, Yan XY, Liu DX, Jin ZM, Wang XJ, Liu LL. Analysis of the friction-induced squeaking of ceramic-on-ceramic hip prostheses using a pelvic bone finite element model. Tribol Lett 2016;61:1-7. doi: 10.1007/s11249-016-0644-4.
62. Hothan A, Huber G, Weiss C, Hoffmann N, Morlock M. Deformation characteristics and eigenfrequencies of press-fit acetabular cups. Clin Biomech (Bristol, Avon) 2011;26:46-51. doi: 10.1016/j.clinbiomech.2010.08.015.