A Study of Wear and Frictional Behavior of Metals and Polymers in Total Hip Arthroplasty : A Review

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Abstract--Wear is recognized as the most important limitation to long term stability of Hip devices. Wear occurs when two surfaces in contact are subjected to a relative motion. The advancement in biotechnology has successfully converted the conventional bearing couples into artificial joints, however the materials used today have not been satisfactory. Problems such as osteolysis and aseptic loosening lead to failure of artificial joints. This paper will review the various ways of increasing the lifespan of the joints and improving current biomechanical understanding of failure modalities in Total Hip Arthroplasty (THA)

INTRODUCTION

Total hip arthroplasty (THA) is the treatment of choice to relieve joint pain andloss of mobility as a result of end-stage osteoarthritis or other severe hip pathologies, andis widely considered to be one of the most successful surgical inventions in all of medical history. Currently, 5lac (approximately) hip replacements are done in UK and around 2 lac (approximately) in United States, every year. Similarly more than 7 lac (approximately) knee replacements are done every year in UK and around 5 lac (approximately) in United States. In India the figure is around 30,000(approximately) total hip replacements every year and in Kashmir its 800-1000 a year, this is a figure which is expected to double in the next 20 years. Over many decades of innovation, hip replacement has seen continual advances; however, the rates of failure, measured in terms of diagnoses requiring a revision surgery, have actually increased in recent years, underscoring the need to further our understanding of THA failure mechanisms. Historically, the most common cause of failure in conventional THA has been from loosening of the implant (osteolysis) due to immunological reaction to polyethylene wear. Efforts to reduce wear have led to a recent shift toward advanced low wear bearing couples for THA. As a result, implant dislocation is now the most common cause of failure. While successful in reducing failure due to osteolysis, these advanced THA designs are susceptible to their own novel failure mechanisms. However, mechanistic information regarding these failure modalities are under-investigated relative to their burden of morbidity. Therefore, the objective of this review paper is to look at the biomechanical understanding of failure mechanisms in contemporary THA.

LITERATURE REVIEW

The total hip arthroplastic surgery was a major medical advance of the 20th century. The materials used in this medical application must possess satisfactory mechanical properties such as stiffness and fatigue strength, wear and corrosion resistance, and biocompatibility. The first metal-on-metal (MOM) total hip prostheses implanted during the1960s decade presented unsatisfactory short-term performance due to geometrical in accuracies which led to high frictional forces and increased wear [1–5]. However, in some cases the implants lasted at least for two decades without osteolysis [2, 5–7] and negligible wear [2, 8–11]. The use of second generation Co–Cr alloy metal-on-metal bearing joints in total hip arthroplasty surgery represents an attractive alternative to the traditional metal- on-polyethylene pairs [12]. Despite the triblological pair metal-on-metal has proven to be more wear resistant than metal-on-polyethylene couple, the toxicity of metallic ions of cobalt and chromium released from wear particles from metal-on-metal hip prostheses into the human body [13–16] is a concern which has motivated to look for alternatives to solve or diminish this problem. In recent years, polymer composites have been extensively used to replace metal materials in engineering applications involving wear and friction. The advantages of polymers such as self-lubricity, being light weight, corrosion resistant and ease of processing have allowed them to be the preferable choice. Being a distinctive polymer which possesses the highest wear resistance compared to any other polymers [17], ultra high molecular weight polyethylene (UHMWPE) was commonly utilized in engineering applications where wear and friction is a concern. UHMWPE has become one of the most modified polymers in the industry, replacing the existing conventional polymers due to its wear resistant characteristics, bio-compatibility [18,19]; low friction [19], chemical inertness and high impact resistance [20]. The wide applications of UHMWPE include bio-medical material for artificial joint replacement [21–23], engineering bearing [24], valves and automotive [17, 24]. Despite the suitability of UHMWPE for these applications, there are still challenges on the wear problem that occur in UHMWPE components, especially in bio-medical implant [24]. To overcome this problem, UHMWPE composites were fabricated by adding reinforcing fibers and particle fillers. Numerous researches have been conducted using fillers in UHMWPE specially for improving its wear behavior in artificial joint replacement. This includes the addition of carbon fiber [19], kaolin [23], natural coral particles [25], zirconium particles [22], TiO2 [26], Al2O3 [27], CNT [28], Pt-Zr quasi crystal [29], hydroxyapatite [30], bovine bone hydroxyapatite (BHA) [31], etc. Studies have shown that the addition of an optimum amount of micro and Nano scale of fibers, in organic particles, ceramic and bio-material into a UHMWPE matrix would significantly reduce the wear rate under sliding wear conditions.

METAL- ON-METAL (MOM)

Metal-on-metal (MoM) articulations have been seen as one potential solution to the problems associated with polymeric particle induced osteolysis. The observation that a small number of patients with first-generation MoM THR (the McKee-Farrar prosthesis in 1960s [21]) exhibited good clinical and radio graphical results after 20 years in vivo have led to the development of second generation MoM hip prostheses, and in 1988 the Metal prosthesis (CoCr on CoCr) was introduced into clinical practice [6]. The MoM total joints usually have ball components with ball diameter 28-32 mm. The remarkable tribological performance of the current MoM total replacement joints is attributable to improved materials, excellent manufacturing procedures and careful design of the head radius and the clearance. Despite the improvement in the design and performance of the hip replacements, prevention of premature failure of hip implants is a continuing problem for physicians and orthopedic engineers. Indeed, the lifespan of hip implants (normally 10-15 years [22]) is significantly lower than the 30-year goal set by the orthopedic community. Over the past 10-30 years, researchers have experimented with various bearing surfaces in an attempt to evaluate the wear performance of artificial hip joints and therefore prolong their lives. The self-mating MoM articulation shows relatively low volumetric wear (lower than MoP and CoP) and friction coefficients comparable to other orthopedic bearing materials [23]. However, low volumetric wear values do not necessarily correspond with a low number of wear particles. With an average size far below 1 µm, it has been estimated that up to 1014 particles could be released from a MoM articulation each year and subsequently these will migrate into the surrounding tissue [24]. Although in vitro cell culture studies have shown that various nanometer sized metal particles are potentially damaging to living cells at relatively low concentrations, these submicron sized metal particles have very limited capacity to activate macrophages to produce osteolytic cytokines at the volumes likely to cause bone resorption in vivo [24]. However, metal particles are not biologically inert and concerns exist regarding their potential genotoxicity. Elevated metal-ion levels associated with the corrosion process have been observed in patients with MoM joints [25]. However the boundaries between normal and toxic levels of the metal-ion concentrations are not as yet fully established and are still being investigated. Therefore, concern with metal debris and metal-ions and their potential toxicity still remains. The available data are insufficient to address the above concerns, and long-term studies are necessary to determine if the benefits of MoM bearings outweigh the associated risks.

METAL-ON-POLYMER (MOP)

John Charnley first conceived the use of MoP bearing surfaces in 1959. His design, known as the Charnley Low Friction Arthroplasty (LFA) comprised a monolithic stainless steel stem and head, which articulated against a polytetrafluoroethylene (PTFE) acetabular cup. The design was engineered to minimize frictional torque, by combining low sliding friction with a small head diameter of just 22.2mm. Although the design produced very low friction, the wear rate limited the life of design to around 3 years. For this reason PTFE was replaced with Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) which greatly improved its wear resistance. The low friction arthroplasty was a huge success for many years, considered by many to be the gold standard of total hip replacements. The maximum life of these prostheses was usually determined by the rate of polymeric wear; this gave an average life span of approximately 16 years, although some report suggest that survivorship could greatly exceed this on occasion.

CERAMIC-ON-CERAMIC (COC)

Ceramic-on-ceramic bearings were first conceived by Boutin in the 1970s[26, 27]. Despite initial popularity in Europe the design had lost favor by the1980s due to issues with fracture and fixation [27]. By the 1990s,improvements in manufacture headed to the development of high purity alumina with reduced grain sizes [26, 28, and 29]. This new generation of ceramics were more resilient to fracture and contributed to the renewed popularity of CoC THRs [1]Ceramic-on-ceramic bearings are renowned for their outstandingly low volumetric wear rates. They produce considerably lower wear rates than: MoP, CoP and even MoM designs [26, 27, and 30]. The superior wear resistance of CoC bearings can be partly attributed to their extremely hard surfaces (7.6GPa<Vickers hardness<17.5GPa) [31, 32], and low surface roughness (5nm<Ra<10nm)(23, 26). It has been shown that, like MoM bearings, MoC bearings also exhibit a 'running-in' period. After this, a shift towards partial or full fluid film lubrication is made [26, 29]. The wear debris produced in CoC contacts tends to be of the nanometer scale [30], and is generally much less biologically reactive than MoP particles [30, 28].Despite these developments, there are some concerns with the performance of CoC bearings. Improvements in material manufacture have not completely eliminated the risk of femoral head fracture. In addition, stripe wear and grain pull-out has been identified on the surfaces of ceramic bearings [27, 29], which may be a concern for long-term implantation.

CERAMIC-ON-POLYMER (COP)

An alternative soft-on-hard bearing combination to MoP is CoP. These consist of an acetabular cup made of UHMWPE and a femoral head made from either alumina or zirconia. The ceramic surfaces used are smoother and harder than their metal counter parts, which results in a reduction to the volumetric wear of the polymer cup [26, 30]. Zirconia is used in conjunction with alumina because of its superior fracture toughness [26].

CONCLUSION

Based on the experiments and case studies which have been reviewed in this paper it has been concluded that although the Metal on Metal bearing couple is a good choice for THA but it has a backdrop of having metal debris and metal-ions and their potential toxicity still remains. In case of MOP the UHMWPE has better wear resistant characteristics, bio-compatibility low friction, chemical inertness and high impact resistance but has a low fracture toughness and the high wear debris generation causing osteolysis and aseptic loosening in THA. Therefore it is required to study more about these materials and joints so that their lifespan and the quality is increased.

REFERENCES

[1] S.Scholes, S.Green, A.Unsworth,The wear of metal-on-metal total hip prostheses measured in a hip simulator, Proceedings of the Institution of Mechanical Engineers Part H215 (2001) 523–530.

[2] H.Amstutz, P.Grigoris, Metal on metal bearing in hip arthroplasty, Clinical Orthopaedics 329(1996)11–34.

[3] G.McKee, Total hip replacement—past, present and future, Biomaterials 3 (1982) 130–135.

[4] P.Walker, B.Gold, The tribology (friction, lubrication and wear) of all metal artificial hip joints, Wear 17 (1971) 285–299.

[5] S.Jacobsson,K.Djerf,O.Wahlstrom,20yearsresultofMcKee – Farrar vs. Charnley prosthesis, Clinical Orthopedics 329(1996)60–68.

[6] B.Weber, Experience with metasul total hip bearing system, Clinical Orthopedics 329(1996)69–77 and S78-88..

[7] B.Weightman, I.Paul, R.Rose, S.Simon ,E.Radin, A comparative study of total hip replacement prostheses, Journal of Biomechanics 6(1973)299–311.

[8] R. Mc Calden, D. Howie, L. Ward, Observation of the long term behavior of retrieved McKee-Farrar total hip replacements implants, Transactions of the Orthopedic Research Society 20 (1995) 242.

[9] H. Mc Kellop, P. Campbell, S. Park, Wear of retrieved metal–metal implants after two decades of clinical use, Transactions of the Combined Orthopaedic Research Societies 2 (1995) 228.

[10] H. McKellop, S. Park, R. Chiesa, In vivo wear of three types of metal on metal hip prostheses during two decades of use, Clinical Orthopaedics 329 (1996) 128–140.

[11] M. Schmidth, H. Weber, R. Schon, Cobalt Chromium molybdenum metal combinations for modular hip prostheses, Clinical Orthopaedics and Related Research 329 (1996) 35–47.

[12] K. Brummitt, C. Hardaker, Estimation of wear in total hip replacement using a ten station hip simulator, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 210 (1996) 187–190.

[13] J. Firkins, J. Tipper, M. Saadatzadeh, E. Ingham, M. Stone, R. Farrar, J. Fisher, Quantitative analysis of wear and wear debris from metal-on-metal hip prostheses tested in a physiological hip joint simulator, Bio-Medical Materials and Engineering 11 (2001) 143–157.

[14]J.Jacobs,A.Skipor,P.Doorn,P.Campbel,T.Schmalzried,C.Amstutz,Cobalt and chromium concentrations in patients with metal on metal total hip replacements, ClinicalOrthopaedics329(1996)S256–S263.

[15] P.Doorn, J.Mirra, P.Campbell, H.Amstutz, Tissue reaction to metal on metal total hip prostheses, Clinical Orthopedics 329(1996)S187–S205.

[16] M.Germain, J.Matthews, M.Stone, J.Fisher, E.Ingham, The effect of clinically relevant cobalt–chrome particles on the viability of human peripheral blood mononuclear cell and fibroblast invitro, in :Proceedings of the Transactions of the 16^{th} meeting of the European Society forBiomaterials,2001,p.76.

[17] H.L. Stein, Ultra high molecular weight polyethylene (UHMWPE), Engineered Materials Handbook (1999) 167–171.

[18] D. Xiong, S. Ge, Friction and wear properties of UHMWPE/Al2O3 ceramic under different lubricating conditions, Wear 250 (2001) 242–245.

[19] P.S.M. Barbour, M.H. Stone, J. Fisher, A study of the wear resistance of three types of clinically applied UHMWPE for total replacement hip prostheses, Biomaterials 20 (1999) 2101–2106.

[20] D. Xiong, Friction and wear properties of UHMWPE composites reinforced with carbon fiber, Materials Letters 59 (2005) 175–179.

[21] G.K. Mckee, J. Watson-Farrar, Replacement of arthritic hips by the Mckee-Farrar prosthsis, Journal of Bone & Joint Surgery 48 (B) (1966) 245-259.

[22] Jin, Z.M., Dowson, D., Fisher, J., Analysis of fluid film lubrication in artificialhip joint replacements with surfaces of high elastic modulus. Proceedings of theInstitution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,1997. 211(3): p. 247-256.

[23] P.F. Doorn, P.A. Campbell, J. Worrall, P.D. Benya, H.A. McKellop, H.C. Amstutz, Metal wear particle characterization from metal on metal total hip replacements: transmission electron microscopy study of periprosthetic tissues and isolated particles, Journal of Biomedical Materials Research 42 (1998) 103-111

[24] Z.M. Jin, M.H. Stone, E. Ingham, J. Fisher, Biotribology, Current Orthopaedics 20 (2006) 32-40.

[25] Hanawa, T., Metal ion release from metal implants. Materials Science and Engineering, 2004. 24(6-8 SPEC ISS): p. 745-752.

[26] Dowson D. New joints for the Millennium: wear control in total replacement hip joints. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine. 2001;215(4):335-58.

[27] Rieker C, Konrad R, Schon R, editors. In vitro comparison of the two hard-hard articulations for total hip replacements2001: Professional Engineering Publishing Ltd.

[28] Roualdes O, Duclos M-E, Gutknecht D, Frappart L, Chevalier J,Hartmann DJ. In vitro and in vivo evaluation of an alumina-zirconiacomposite for arthroplasty applications. Biomaterials. 2010;In Press,

Corrected Proof.

[29] Vassiliou K, Scholes SC, Unsworth A. Laboratory studies on thetribology of hard bearing hip prostheses: ceramic on ceramic and metal onmetal. Proceedings of the Institution of Mechanical Engineers, Part H(Journal of Engineering in Medicine). 2007;221(H1):11-20.

[30] Tipper JL, Hatton A, Nevelos JE, Ingham E, Doyle C, Streicher R, etal. Alumina-alumina artificial hip joints. Part II: Characterization of the wear debris from in vitro hip joint simulations. Biomaterials. 2002;23(16):3441-8.

[31] Kumar P, Oka M, Ikeuchi K, Shimizu K, Yamamuro T, Okumura H, etal. Low wear rate of UHMWPE against zirconia ceramic (Y-PSZ) in comparison to alumina ceramic and SUS 316L alloy. Journal of Biomedical Materials Research. 1991;25(7):813-28.

[32] Costa HL, Pandolfelli VC, de Mello JDB. On the abrasive wear of zirconias. Wear. 1997;203-204(0):626-36.