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A Briefing on the Manufacture of Hip Joint Prostheses

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Abstract. To produce lifelong, harmless hip joint prostheses, considerable cross-disciplinary studies have been carried out. The research includes adaptability and sustainability of artificial materials to human body, selection of materials, precision fabrication and efficient replacement operation. This paper provides a brief review of some of these key aspects with some details in abrasive polishing.

Design and Characterisation

Background. The percentage of elderly people is growing rapidly in the developed world [1], which has tremendously increased the healthcare demand. There are more than 21% of adults in the United States [2], more than 100 million people in Europe and about 16.7% of the population in Australia who have arthritis or have suffered from arthritis [3, 4]. Sometimes, a total hip replacement has to be carried out to replace the arthritic hip joint with an artificial one, as illustrated in Fig.1 [5, 6, 7], to release the pain or recover the joint function. However, most of the hip prostheses have a limited lifespan from about 5 to 15 years. Dislocation, loosening, infection and wear are some of the problems.

The design of hip joint prostheses must vary to cater for different demands. The size of the femoral head shown in Fig. 1 ranges generally between 22 mm to 40 mm in diameter to suit individual patients. To improve the performance of the total hip prostheses, significant studies have been carried out in the areas such as better manufacturing processes, new stem designs and more accurate means for characterisation. In the following, we will first highlight some important issues and then focus on polishing as the precision finishing step of the prostheses manufacturing.

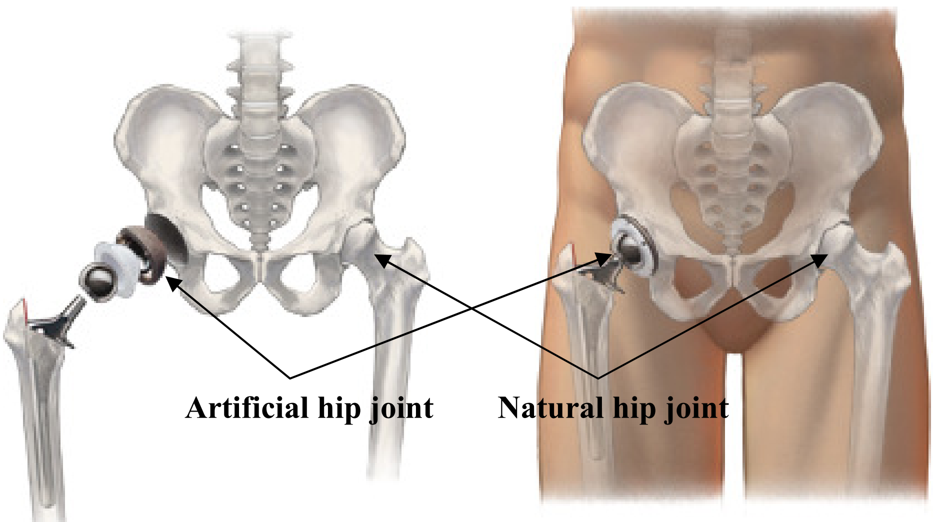

Fig.1 Total hip replacement (http://zimmer.com.au).

Design and manufacture requirement. To improve their longevity, the design of hip joint prostheses needs to consider the following factors:

Femoral head and acetabular cup. A hip joint prosthesis consists of two central parts, a femoral component, which has a ball head, and an acetabular element, which is a shell with an inner socket liner, as shown in Fig.2. The ball of the femoral that fits inside the socket is to enable the articulation of hip joint like a mechanical bearing. The materials for hip joint prostheses must have the following properties: **(*a*)** high biocompatibility with tissues and bones; **(*b*)** sufficient mechanical strength, *e.g.*, suitable Young's modulus, fracture toughness and fatigue life; **(*c*)** low friction but high wear resistance; and **(*d*)** reliable chemical stability and safety. Wear of hip joint prosthesis is related to the materials used and the head diameter [8-13]. For instance, in a metal-on-polyethylene bearing couple, a larger femoral ball wears faster [11], although a larger head increases the range of motion and reduces dislocation [12]. From the manufacturing point of view, it is essential that the bearing surfaces of the femoral ball and acetabular socket needs to have a high grade of surface finish and to maintain a high engagement stability of bearing when a patient takes different kinds of motion. These can only be achieved by a well-designed fabrication technology to be discussed later.

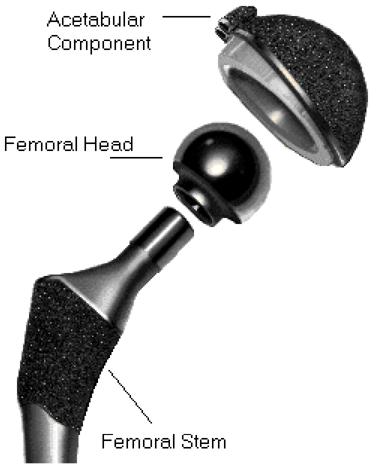

Fig.2 The fundamental hip join bearing components [14]

Range of motion. This depends on a patient and is often related to the culture of a particular region. In some areas of the world, for instance, many activities are performed while squatting and sitting cross-legged, demanding a greater range of motion [15]. A design with an insufficient range of motion will lead to impingement of the femoral neck on the acetabular cup. From the surface polishing point of view, hip joint prosthesis with a bigger range of motion is more difficult to finish.

Stress. A hip stem can experience complex stressing, for example, during chair rising and stair climbing. In general, a vertical load on the femoral component produces a compressive stress on the medial side and a tensile stress on the lateral side of a hip stem. An anterior load results in shear stresses at the prosthesis-bone and prosthesis-cement-bone interfaces. Studies on the hip contact force, muscle joint force and torque [16-18] reported that the force in a hip joint in fast walking and stairs climbing could be up to eight times of the body weight of a patient. Hip joint prostheses need to be designed to sustain such stressing.

Stem. A femoral stem (Fig.2) is to ensure the long term fixation of prosthesis to the bone, and must be able to withstand under complex stresses. If a stem design will lead to high stresses in the fixation zone, fracture or fatigue failure is likely to occur, although a thin neck gives a greater range of motion without the impingement against the acetabular cup. Since stem manufacture is not the scope of this paper, its design considerations are skipped here. The reader can refer to the literature for details [19-20].

Characterisation and assessment. A new design of hip joint prostheses must be assessed, often on a simulator (Fig. 3), to examine its longevity in terms of its fatigue strength and wear life in relation to head-sleeve sliding, debris-trapped abrasion and non-bearing surfaces rubbing, through the motion simulations of walking, stair climbing, swing or dislocation g [21-30].

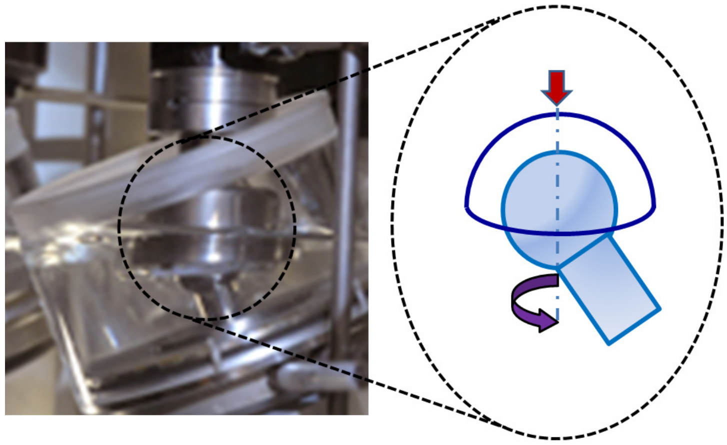

Fig. 3 The motion in a hip joint simulator (left image: https://www.beaumonthospitals.com).

Manufacture

Fabrication processes in general. The process selection for fabricating a total hip prosthesis depends very much on the materials to use. Materials such as cobalt chrome, titanium and stainless steel are usually shaped by forging or investment casting, followed by rough machining, polishing and coating. For materials such as ultra-high molecular weight polyethylene, moulding and machining are essential. Ceramic biomaterials elements, such as alumina and zirconia femoral balls, are normally produced by sintering followed by grinding and polishing/lapping. Some details can be found in Ref. [31-32]. Since shape accuracy, surface roughness, and surface integrity of the prostheses play key roles in their longevity, and since these are mostly achieved by polishing, we will discuss more about polishing in the manufacture of hip joint prostheses.

Polishing. The bearing surfaces of the femoral ball and acetabular socket needs to have a high grade of surface finish and to maintain a high engagement stability of bearing when a patient takes different kinds of motion. Such high quality bearing surfaces can be produced by polishing. In the past, the polishing process had been manual, which was cost-ineffective, labour-intensive and hard to guarantee the dimensional accuracy such as the roundness and consistency in mass production. This situation has been significantly improved through the development of sophisticated lapping and polishing machines for spherical balls and cups to a roundness of about 2 microns and surface roughness of a fraction of nanometers [33-38].

To improve the efficiency, the polishing and lapping should be integrated with a CNC process, of which the control relies, to a great extent, on a uniform material removal over the whole area to polish. A good process can precisely maintain the geometrical accuracy of the surface generated by pre-polishing shaping, such as forming, cutting and grinding. To reach this, it is essential to understand and to be able to manipulate the trajectories of the abrasive cutting edges on a workpiece surface during polishing. Studies aiming at the mechanism understanding and process automation of such polishing have been carried. Sun and Zhang et al [39] used the finite element method to analyze the polishing trajectories on spherical lenses. They also conducted some experimental investigations [40] which enabled them to derive an empirical formula to evaluate the material removal. Following this approach, Kiat [41] analyzed the combined trajectories of multiple cutting edges of a polishing tool (A, B, C and D on the external spherical surface in Fig. 4) on the workpiece surface (spherical ball in Fig. 4). They found that under certain combinations of the three angular velocities, some portions of the workpiece areas will be missed out; but under some other velocity combinations, the whole surface can be uniformly polished, as shown in Fig. 5, where the colored areas represent the corresponding trajectories made by the cutting edges denoted by the same colors in Fig. 4.

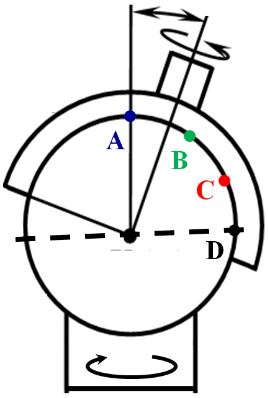

Fig. 4 A spherical polishing system with three independent angular velocities.

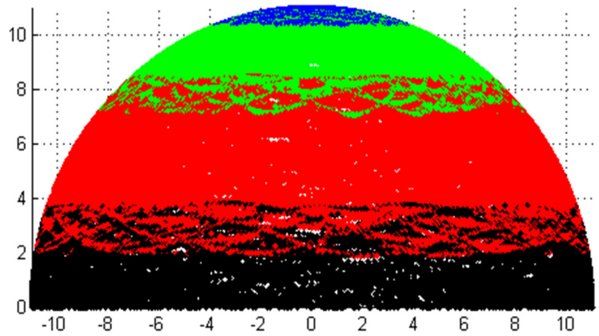

Fig. 5 The combined trajectories of cutting edges A, B, C and D in Fig. 4 on the sphere subjected to polishing [41].

A numerical analysis such as the above can hardly provide an optimized solution for the abrasive trajectories with respect to the change of kinetic parameters of a polishing. An experimental model, on the other hand, is often limited by the range of testing conditions. To overcome these difficulties, Li, Bao and Zhang [42] recently developed an analytical solution for describing the trajectories of abrasives in polishing a spherical surface. They found that the trajectory coverage on a spherical surface by individual abrasives relies very much on the kinetic parameters such as the rotational angular velocities of the specimen and polisher. If these kinetic parameters are inappropriately selected, a uniform material removal status cannot be achieved.

Concluding remarks

Hip joint replacement provides a solution to deal with arthritis. The range of motion, stress, head diameter and stem of hip joint prostheses are important factors to consider in the design of artificial hip joints. CNC polishing is an important manufacturing step to maximise the performance of the prostheses. However, there is much to be done to optimise the abrasive polishing process.

References

[1] P. Charlton, L. Blunt: Wear Vol. 264 (2008), p. 399
[2] http://www.cdc.gov/arthritis/ data_statistics/national_data_nhis.htm
[3] http://www.arthritiscare.org.uk/PublicationsandResources/Arthritisbasics /Arthritisstatistics
[4] http://www.nevdgp.org.au/info/ArthritisF/ArthritisCosts.pdf
[5] H.Malchau, P.Herberts, L. Ahnfeit: Acta Orthop Scand Vol. 64 (5) (1993), p. 497
[6] O.A. Nercessian, et al: J. Arthroplasty Vol. 20(2) (2005), p. 162
[7] M.M. Mullins, et al: J. Arthroplasty Vol. 22(6)(2007), p. 833
[8] A. Gandhe, and M.Grover: Current Orthop. Vol. 22 (2008), p. 155
[9] J.Livermore, D. Ilstrup, and F. Morrey: J Bone Joint Surg. Vol.72(4) (1990), p. 518
[10] JM Kabo et al.: J. Bone Joint Surg. Vol. 75(2)(1993), p. 254
[11] BF Morrey and D. Ilstrup: J. Bone Joint Surg. Vol. 71(1)(1989), p. 50
[12] D. Kluess, et al.: Med. Eng. Phys. Vol. 29(4)(2007), p. 471
[13] A. Reinhardt, et al.: J. Compos. Mater.Vol. 33(9)(1999), p. 870
[14] http://www.healthpages.org/

[15] S.J. Mulholland and U.R.S.P. Wyss: Int. J. Rehabil. Res. Vol. 24(3) (2001), p.191
[16] G. Bergmann, et al.: J. Biomech. Vol. 34(7) (2001), p. 859
[17] G. Bergmann, F. Graichen and A. Rohlmann: J. Biomech. Vol. 26(8)(1993), p. 969
[18] J.P. Paul: Proce of the Royal Society of London. Biological Scie Vol. 192(1107) (1976), p. 172
[19] B.J. McGrory, et al.: J. Bone Joint Surg. British Volume Vol. 77(6) (1995), p. 869
[20] A.Z. Senalp, O. Kayabasi and H.Kurtaran: Mater. Design Vol. 28(5) (2007), p. 1583
[21] H.A. McKellop et al.: J. Ame. Aca. Ortho. Surg. Vol. 16 (2008), p. 119
[22] V. Saikko: J. Biomed. Mater. Res. Vol. 41(1)(1998), p. 64
[23] VA González-Mora et al.: Mater. Sci. Eng. C Vol. 29(1)(2009), p. 158
[24] C.C. Hu, et al.: Mater. Sci. Eng. C Vol. 17(1-2) (2001), p. 18
[25] J. Davidson, S. Gir and J.P.Paul: J. Biomed. Mater. Res. Vol. 22(1988), p. 309
[26] M. Jasty, et al.: J. Bone & Joint Surgery, British Vol. 73(4) (1991), p. 558
[27] J.P. Hung, et al.: Comput. Method. Program. Biomed. 76(2) (2004), p. 113
[28] J.R.T. Jeffers, et al.: J. Biomech. Vol. 40(7)(2007), p. 1533
[29] D. Bennett, et al.: Proce of the 22nd Annual International Conference of the IEEE. Vol.22000
[30] O. Calonius and V.Saikko: Acta Polytech. Vol. 43(4)(2003), p. 54
[31] J.Breme, et al.: Handbook of Biomaterial Properties. Kluwer Academic Publishers, (1998), p. 135
[32] M. Dietrich: Proceedings 10th International BIOLOX Symposium, Springer, Darmstadt, (2005), p. 173
[33] C.N. Ernsberger: European patent-EP 1 905 387 A1. https://publications.europeanpatentoffice.org/PublicationServer/getpdf.jsp?cc=EP&pn=1905387&ki=A1 (2008)
[34] M. Semlitsch, C.H. Winterthur: United States Patent 6126695 (2000)
[35] F. Lin and T. Lu: Proceedings. International Conference on Intelligent Mechatronics and Automation (2004), p. 980
[36] http://www.faqs.org/patents/app/20080215158
[37] http://www.wipo.int/ pctdb/en/wo.jsp?wo=2002004696, (2002)
[38] http://www.lapmaster.co.uk /machinery/lapping-polishing machinery/spherical/default.html
[39] J. Sun, L.C. Zhang, Y.-W. Mai, J.A. Gal, M. Hogg, S. Payor: J. Mater. Process. Technol. Vol. 122 (2000), p.134.
[40] J. Sun, L.C. Zhang, Y.W. Mai, J.A. Gal, M. Hogg and S. Payor: J. Mater. Process. Technol. Vol. 103 (2000), p. 236.
[41] E.C.S. Kiat: Internal Project Report, School of Aerospace, Mechanical & Mechatronic Engineering, The University of Sydney, Australia (2009)
[42] H.F. Li, R.H. Bao, L.C. Zhang: Adv. Mater. Res. (2009) under review.

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