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RESEARCHING AND TRENDS IN OPTIMIZING HIP JOINT PROSTHESIS

Abstract: *Nowadays the biomechanical field is getting a significant amplitude and the research directions from all over the world are increasingly focusing on the prostheses personalization. In T.H.R. (Total Hip Replacement) the most important factors that lead to a good osseointegration are the design and implicitly hip prosthesis geometry, the prosthetic components orientation, the couple type and the biomaterials used; bone quality and the patients' medical history, as well as the surgeons' approaching method in orthopedics may influence the outcome of the hip replacement surgery also.*

From the first hip implants initiated by Temistocles Gluck between 1853 and 1942 and up to nowadays implants that attempts to reproduce femoral geometry and bone structure, this article aims to present the most important evolutionary stages of hip prostheses and the optimization directions that researchers approach ultimately.

Key words: *hip joint, prostheses, implant, hip stem, total hip replacement*

1. CONTEXT

Hip Replacement is one of the most common orthopaedic surgery nowadays due to increased demand in that sense. The aging is one of the factors that leads to hip replacement because in time the body capacity of cellular regeneration is reduced, due to multiple implications, so bone tissue begins to suffer transformations such as bone demineralization. In time the hip joint suffers severe transformations making possible the appearance of most frequent hip joint disease, osteoarthritis.

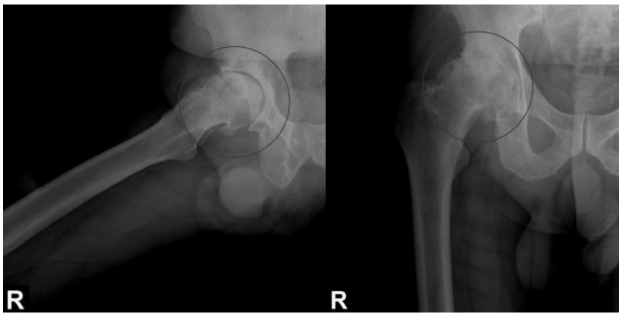

Fig. 1 Hip joint affected by osteoarthritis (Image Source: Emergency University Hospital Bucharest).

According to Swedish Hip Register between 1992 and 2003 primary osteoarthritis is present at 52% of patients under 50 years, 78.2% for patients with age between 50 and 59 years, 80.5% for patients with age between 60 and 75 years and 66.9% for patients with an age higher than 75 years. Other important factors which lead to hip replacement surgery are the: increasing of outdoor and indoor sports activity, weight increasing, unhealthy diet, physical inactivity, trauma caused by injury, hereditary diseases and so on. These types of factors may cause the following diagnoses that in time can require a hip joint replacement: bone fracture (11.4%), inflammatory disease such as bursitis (4.6%), avascular necrosis (2.9%), childhood disease (1.6%), tumour (0.4%) and traumatic osteoarthritis (0.3%) [1].

Considering the joint problems that can occur during life time, orthopaedic surgeons and engineers worked together to develop implants that imitate the human hip joint. Because of the bone morphological complexity the junction between the pelvis and the femur was reduced to a ball and socket geometry, in order to accomplish the transmission of body weight from the pelvis to the femur and to support the leg oscillation during the daily-life movements.

2. HIP JOINT PROSTHESIS EARLY EVOLUTION

Although the oldest exo prosthesis in the world was discovered in Luxor in 2000 being dated around 950 – 710 B. C., and representing a thumb toe wooden foot finger [2] (the foot thumb toe is responsible of carrying our ~40% weight of the body) [3], the endoprosthesis evolution did not enjoy such an early progress due to precarious knowledge of the human body reaction at foreign objects implantation, which is particularly related to the materials biocompatibility.

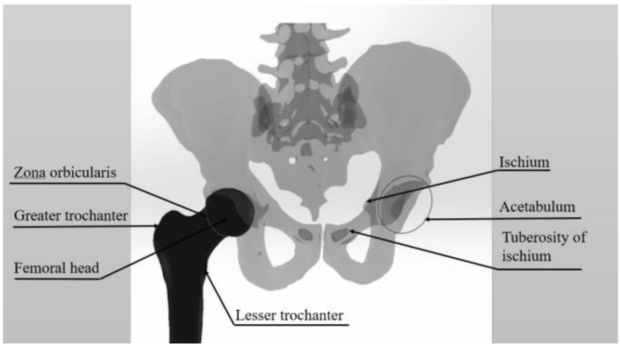

Fig. 2 The articular structure of human hip joint.

The idea of developing an endoprosthesis appeared in the early 1960s in order to help patients suffering from various bone tissue tumors who had to undergo amputation surgeries, being the safest and valid solution at that time, and, in this sense, the orthopaedics pioneers developed various techniques in this regard which unfortunately failed [4].

Meanwhile, the need for lower limb endoprosthesis development is increasing, and the first proximal femoral replacement has been successfully accomplished by Themistocles Glück (30 November 1853 in Iasi, Romania - 25 April 1942 in Berlin, Germany) in 1981 by using a piece of ivory to replace the femoral head of a patient [5] and in the same year he tries a cemented technique by using methacrylate bone cement [6].

After this success, other orthopaedic surgeons tried to find another more feasible material for joint implants, so in 1925 the American surgeon Marius Nygaard Smith-Petersen develop the first mold arthroplasty made out of glass which proved to be a real failure due to the fragility of the material and not because of biocompatibility because glass is a highly compatible material with the human body [7].

Later on is Sir John Charnley (29 August 1911 – 5 August 1982), a British orthopaedic surgeon who introduced the "low-friction artroplasty" based on a MOP (Metal on Polyethylene) bearing couple. [8] Inspired by the idea of Glück, he also uses the cement from dentist in order to improve the prosthesis fixing which proved to be a success [9].

Charnley began the rise of modern arthroplasty which we know today, after his principle many engineers and surgeons have tried to develop different bearing couples made of various biocompatible materials and try to imitate as much as possible human anatomical morphology.

3. ELEMENTS AND BEARING COUPLES OF HIP JOINT PROSTHESIS

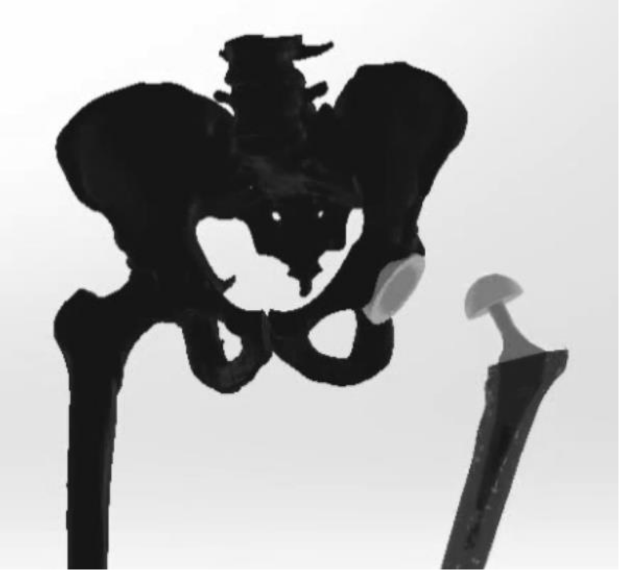

Fig. 3 Total Hip Replacement (Bipolar Hemiarthroplasty). Virtual Surgery

The hip joint arthroplastic surgeries can replace a part of the damaged hip joint (Unipolar Hemiarthroplasty) with a particular prosthetic component, or it can replace the entire damaged hip joint with a new prosthetic one (Bipolar Hemiarthroplasty) [10] that is called Total Hip Replacement (T.H.R.) and which we will focus on this paper.

Materials commonly used for hip prosthesis manufacturing must have certain properties, such as: biocompatibility in order to avoid human body side effects like prosthesis rejection, an excellent resistance at corrosion due to the severe environment that is implanted, a good mechanical resistance to be able to withstand repetitive cyclic loading, a low modulus to reduce the bone resorption, such as a high wear resistance to minimize the particle generation.

Prosthetic wear is another important problem caused of the relative motion under load joint surfaces or interface of the surfaces with other modular components. In the wearing process a part of material is removed from the surface during its mechanical process, this means that tensions associated with the destruction process of material surface can overcome, and resistance produce wear particles.

3.1 Hip joint prosthetic components used in T.H.R. surgery

- **<u>Femoral stem</u>** is the prosthetic component that it is inserted into the femoral channel to recreate the femoral neck geometry (Figure 4) and is generally made of various metal alloy [11]. In order to choose the most suitable standard size for the patient needs, the surgeons perform some femoral measurements on the patient's X-Ray and determine the stem type [12].
- **<u>Femoral head</u>** is the prosthetic part pressed fit into the femoral stem neck and designed to recreate the femoral head (Figure 4) [13].
- **<u>Acetabulum shell</u>** is the prosthetic component designed to reproduce the acetabular part of the pelvis being fixed in the patient's pelvis (Figure 4) [14].

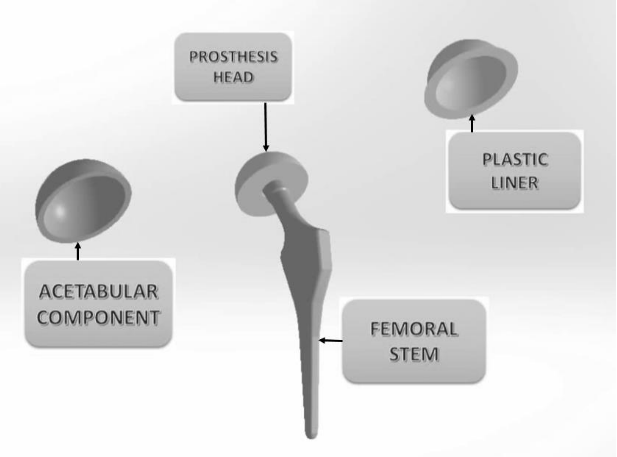

Fig. 4 Hip joint prosthesis general components

- **<u>Acetabulum liner</u>** is the prosthetic element pressed inside the acetabulum shell, usually made of UHMWPE (Ultra High Molecular Weight Polyethylene) and which come in direct contact with the femoral head of the stem, thus recreating the artificial hip joint (Figure 4) [14].

3.2 Prosthetic hip joint bearing couples

There are a variety of hip joint bearing couples, but from the Charnley "low-friction arthroplasty" idea of development, the MOP bearing couple enjoys a great popularity among patients [15].

Type of bearing couples used in T.H.R.:

- **MOM *(Metal on Metal)*** was first developed by Philip Wiles in the 1930s in which the components were fixed with bolts and screws and the material used was steel on steel. Twenty years later MOM is improved by the orthopaedic surgeons McKee and Ring, the British surgeon McKee uses in 1953 a Thompson stem substantially modified. The McKee hip joint prosthetic method was a real success because the average life span was approximately 28 years, with a rate of 74% [16]. The main material used in this type of bearing couple are: stainless steel, cobalt-chromium alloy, cobalt-chromium-molybdenum alloy, titanium alloy. In recent years, the most commonly used metal alloy is the titanium, specifically Ti-6Al-4V known also as TC4 [17] with a good biocompatibility and good mechanical properties, instead the chrome alloy begins to be avoided because the researchers have shown that it can facilitate the onset of cancer [18].
- **MOP (Metal on Polyethylene)** is one of the most widely accepted bearing couple for T.H.R. consisting of metal alloy femoral head in contact with a polymeric acetabulum component. This method was studied especially by Charnley, which between 1958 and 1962 used a cobalt-chromium alloy with PTFE (Polytetrafluoroethylene) fixed with acrylic cement and later on used the cobalt-chromium alloy with UHMWPE fixed with acrylic cement. The precursors of this method were also Oonishi that in 1971 used the UHMWPE of 1000 KGy and Grobbelaar that in 1978 used the UHMPE of 100 KGy [19].

Fig. 5 Titanium alloy hip stem with hydroxyapatite which permits bone ingrowth [TORNIER Linéa^{TM} Anatomique]

- **COC (Ceramic on Ceramic)** was the first developed by Boutin in 1970. Due to ceramics high biocompatibility with the human body, was highly sought after. Later on, in 1977 Shikata used Al_2O_3 with UHMWPE fixed with acrylic cement [20]. The main problem of this bearing couple is that following wear particle which leads to long term toxicity, but also the fact that the ceramic is brittle, so mild trauma can lead to severe prosthesis damage. Most materials used in this bearing couples are: alumina, zirconina, high isostatic pressed alumina and other ceramic alloys.

4. TOTAL HIP REPLACEMENT TRENDS

Along technologization, orthopaedic surgeons and engineers have sought to continuously improve hip endoprosthesis in order to meet the needs of patients.

Because of the increasing of sport activities and also due to an unhealthy lifestyle, people are more and more subjects to T.H.R. from early ages, so one of the problems that researchers are trying to solve is to increase the hip implants life spam in order to reduce the revision surgeries that a patient must undergo during his life. Most of the people have to undergo an revision surgery because of the postoperative complication, such as periprosthetic osteolysis which occurs due to the polymeric component wear that produce debris, this release in the body cytokines and proteolytic enzymes that gradually leads to prosthesis failure [21]. So in order to reduce the polymeric debris, engineers figure out that a polyethylene that passes through a gamma-ray irradiation process are reducing the polymeric prosthetic component wear.

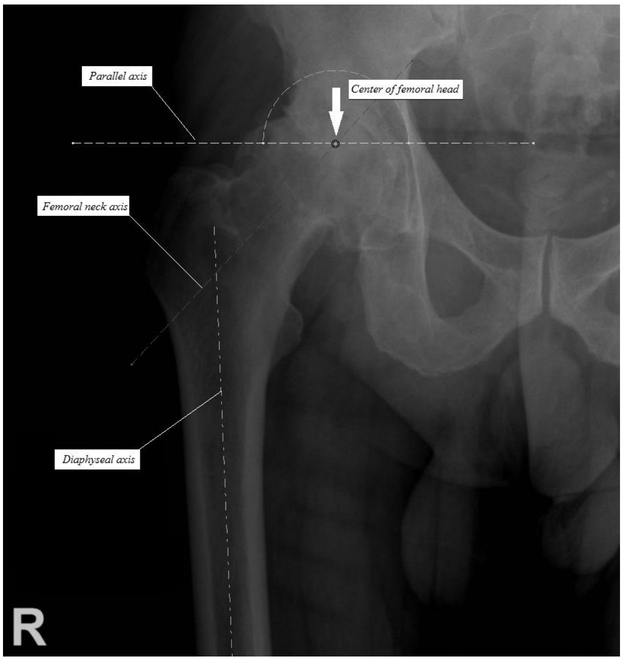

Fig. 6 Axis tracing in 2D preoperative planning

Even if the MOM bearing couples reduce the osteolysis, the wear particles called metallosis (metal ions) has shown that presents a potential carcinogenic risk to patient with hypersensitivity [22].

Nowadays for young active people, researchers developed hybrid endoprosthesis that prevent the pelvic loss presenting special coating such as hydroxyapatite that permits bone ingrowth on the prosthesis allowing a better fixation leaving the surgeons to use a cement less technique [23].

The trend of minimally invasive surgery wants to reduce the time of surgery and prevent blood loss, but also the use of materials and geometries that reduce the percentage of those who have to undergo revision surgeries [24] [25]. For this, engineers are developing computer assisted surgery, software that permits the surgeon to visualize patient's particular case and perform a virtual T.H.R. surgery. This solution comes to help surgeons to understand better if a particular T.H.R. solution or hip joint prosthesis is the best choice for a specific patient subject. Software such as Osso VR was developed to train orthopaedic surgeons and validate orthopaedic surgeries technique in a very realistic way [26].

Another trend in orthopaedic area is also recreating a more faithful prosthetic geometry in order to fit better with patient's thigh bone and horizontal pelvic coxal bone morphology. In this sense engineers inspired by surgeons preoperative planning they try to identify the landmarks that permit to customize the prosthesis [27]. Although initially the first prosthesis were customized (Bohlman and Austin T. Moore 1939) [28], it occur a lot of time to manufacture them and also higher production costs, so this fact led to the hip joint prosthesis standardisation and modularity.

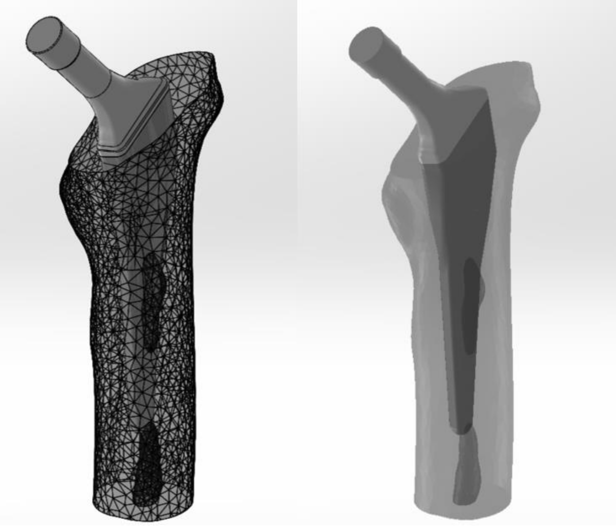

Fig. 7 Custom prosthesis made by extracting patient's femoral landmarks from C.T. scans

Along with advancing technology and the emergence of 3D printers, engineers are trying to develop solutions for personalizing prosthesis by extracting patient femoral landmarks from C.T. (Computer Tomographic), design the endoprosthesis in a dedicated software and manufacture it with 3D printing technology [29]. Software engineers are working on developing semi-automated software that allows surgeons to insert the landmark values and with the help of some algorithms, the software calculates the prosthesis geometry and transmits the information further to the 3D printer in order to manufacture the custom implant [30].

Many studies are also being carried out on biomaterials, the tendencies being to obtain a material with mechanical characteristics as close as possible to human bone tissue [31]. Although initially the idea was to implant prosthesis made of metal alloys from the prism that they will last longer, inserting a much heavier and denser object than the femoral bone tissue that presses the thigh bone and the horizontal pelvic coxal bone, which is subjected to considerable effort every day can damage bone tissues, fracture the femur and causing serious complications that eventually leads to prosthesis failure. In this sense the latest research is done with materials that copy the bone tissue structure and eventually capable to be 3D printed [32] in such a way that the final product presents a gradient of property, just like human bone tissue.

Fig. 8 3D printed hip joint extracted from C.T. scans (made of polymeric material)

Thus, all the orthopaedic and THR tendencies tend to bring hip prosthesis as close as possible to human body articular morphology [33] and to reproduce the structure of bone tissue as accurately as possible so that the final product fits on the patient's needs, providing sustainability and natural walking with the possibility of doing sports.

5. CONCLUSIONS

Starting from the first surgeon, Carnochan, who thought in 1840 that it could replace an unhealthy hip joint with an artificial one, the evolution of hip prostheses underwent positive transformations along with the technology. Although the first prosthetic attempts were a real failure due to materials that were not compatible with the human body, researchers gradually understood how the human body responded to foreign objects and developed an appropriate geometry to replicate the principle of articular functioning and materials which the body accept it easily and do not give side effects over time.

Today virtual prototyping, virtual reality and 3D printing technology give us multiple possibilities to automate procedures that were previously calculated on paper, to pre-plan in a more realistic way a T.H.R. surgery and to achieve endoprosthesis which can replicate as faithfully as possible the hip joint human geometry and tissue structure by attributing its mechanical characteristics equal to the human bone tissue.

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