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OPTIMUM DESIGN OF ARTIFICIAL HIP JOINTS

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Abstract: This paper describes the biomechanics and designing of the hip joint implants, proposes the ideal requirements of a successful hip joint and studies the current existing artificial hip joint designs on the market where it evaluates the best of those products. Regarding to biomechanics of an artificial hip joint it states the forces applied on the joint and lists various hip joint motions. The statistics of artificial hip joint in UK in terms of type of patients, products, procedures and complications have been cited. . Finally the paper reviews the optimisation process with the aid of FEA technique and specifies the main objectives and progress of this project.

1. Introduction.

Arthroplasty is a type of orthopaedic surgery which is used to treat hip disorder by remodeling or realigning the hip joint. It involves replacing the damaged hip joint by restoring the joint coordination The surface is removed (Osteotomy) or shaved off (with a bone saw and chamfer reamers) and is replaced by a prosthetic implant. It helps reduce pain and increases the patients mobility. . Hip replacements are usually carried out on older individuals where the hip joint has worn away after many years. of wear and tear. Once carried out they can last at least 10 years.

Painful hip disorders like arthritis, necrotic joint, fractures, destructions or misalignments of the ball (coxa vara & coxa valga) or the socket, dislocation or failure of previous surgery can be an indication for hip replacement. It should be noted that there are many complications the patient may face after joint replacement such as: loosening, dislocation, severe pain, infection, particle disease (mostly around the screws), polyethylene wear, and component fracture.

The total number of hip procedures during 2008 is 71,367, an increase of 3.6% over 2007. Of these, 64,722 are primary and 6,581 (9%) are revision procedures.

Indications for surgery for single stage hip revision procedures in 2008 in terms of percentage reported as Aseptic loosening 60%, Lysis 18%, Pain 27%, and Infection 3%. The average age of patients is 66.7 years. Approximately 60% of the patients are female. On average, female patients are older than male patients at the time of their primary hip replacement (68.4 years and 65.8 years respectively) (NJR, 2009).

1.1 Ideal Requirements of a Successful Hip Joint.

Ideal hip joint prosthesis should meet some standards like stability, full range of motion, strength and stiffness, & bio compatibility. Unstable hip joints may result in dislocation, whereas a full range of motion should enable the patient to have maximum mobility. Strength and stiffness of the implant can be changed by either type of material or thickness and size of design to decrease high stress concentration in the implant that may cause severe pain. Bio compatibility is the quality of not having toxic or injurious effects on biological systems (Dorland, 1980). Common materials used for different parts of hip joint implants are stainless steel, cobalt chrome, titanium, alumina, zircon, UHM Polyethylene & Ceramic. Many modern implants use Hydroxylapatite as a coating to promote bone ingrowth into the prosthetic implant.

2. Biomechanics of Hip Joint.

2.1 Anatomy of Hip Joint.

The hip joint consists of two main bones, as shown in Figure 1. The femur and pelvis connect together to form the hip joint. The hip joint is a ball and socket joint that helps support the body mass as well as facilitating its movement in many directions. It is important to understand the biomechanics of a hip joint to be able to design an ideal implant. Different aspects such as the amount of various motions of the joint and also types and amount of different forces and movements applied to the joint in various forms should be taken into consideration

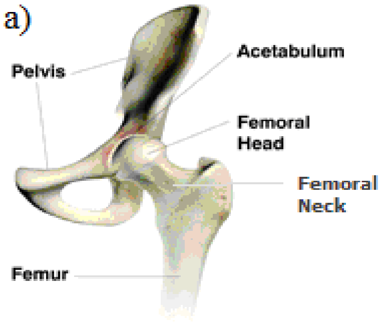

Figure1. Anatomy of Hip Joint.

2.2 Hip Joint Motion.

The range of motion of a joint is controlled by joint positions. Table 1 presents mean values of range of motion for the hip Joint. Basically, the constraints that define a range of motion are the presence, structure and composition of bones, cartilages, ligaments, muscles, fatty tissues and skin.

Two types of range of motion can be considered:

- Active: this is measured when the individual moves the joints independently and this activates the muscles to move.
- Passive: this is measured while the person is resting, a second one uses the individuals hands or a machine to produce movement in the individuals joint (Anderson, 2002).

Yoshimine and Ginbayashi (2002) demonstrated a mathematical formula that is capable of calculating the range of motion for a total hip replacement in a very easy and accurate way. They governed ROM of THR by five factors. (1) Prosthetic ROM (oscillation angle), θ (2) Cup abduction, α (3) Cup anterior opening, β (4) The angle of the neck position from the horizontal plane, *a* (5) The anteversion of neck around the vertical axis (long body axis) from coronal plane, *b*.

Type of Motion	Max angle in degrees
Flexion	120
Extension	30
Abduction	45
Adduction	25
Internal rotation	40
External rotation	45

Table1. Mean Hip Joint Range of Motion (Luttgens and Hamilton, 1997).

2.3 Hip Joint Forces.

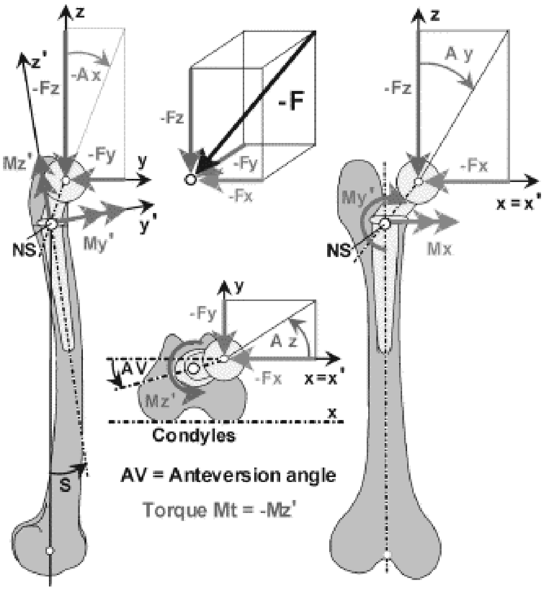

Figure2. Coordinate System at Left Femur (Bergmann et al., 2001).

Bergmann et al. (2001) presented a brief calculation of the mechanical loading and function of the hip joint and proximal femur. The average person loaded their hip joint with 238% BW (percent of body weight) when walking at about 4 km/h and with slightly less when standing on one leg. When climbing upstairs the joint contact force recorded 251% BW which is less than 260% BW when going downstairs. Inwards torsion of the implant is probably critical for the stem fixation. On average it was 23% larger when going upstairs than during normal level walking. The inter- and intra-individual variations during stair climbing were large and the highest torque values are 83% larger than during normal walking.

A typical coordinate system for measured hip contact forces is shown in Figure 2. The hip contact force vector $-F$ and its components $-F_x$, $-F_y$, $-F_z$ acts from the pelvis to the implant head and is measured in the femur coordinate system x, y, z. The magnitude of contact force is denoted as F in the text. The axis z is parallel to the idealized midline of the femur; x is parallel to the dorsal contour of the femoral condyles in the transverse plane. The contact force causes a moment M with the components M_x, $M_{y'}$ and $M_{z'}=-M_t$ at the point NS of the implant. A positive torsional moment M_t rotates the implant head inwards. M is calculated in the implant system x, y', z'. Both systems deviate by the angle S. AV is the anteversion angle of the implant (Bergmann et al., 2001).

One of the major factors to be considered is the loading condition. Some type of loads may have a more significant effect on the design. Biegler et al. (1995) developed a brief FE analysis and calculation of two designs of hip prostheses in one-legged stance and stair climbing configurations. It is shown that torsional loads such as occur during stair climbing contribute to larger amounts of implant micromotion than stance loading does. Contact at the bone-prosthesis interface is more dependent on load type than on implant geometry or surface coating type.

2.4 Design of Artificial hip Joints.

An artificial hip joint consists of two main parts:
1- Femoral stem & Head.
2- Acetabular cup & Liner

In designing the femoral stem there are many points to be considered. The following terms are affecting the Stem designing (Figure 3):

- Head diameter
- Neck diameter
- Neck length
- Neck angle
- Head neck ratio
- Stem length
- Offset

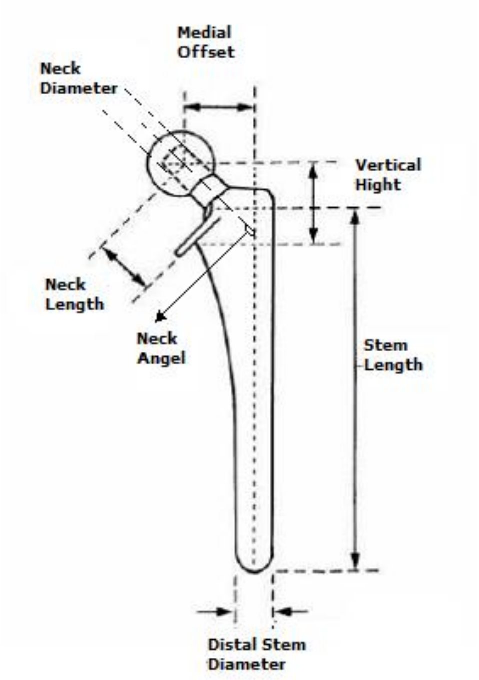

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Figure 3. Schematic diagram of a Femoral Stem

In designing the acetabular cup & liner the main focus should be stability and the use of appropriate material. The acetabular cup is produced from metal or ceramic materials while the liner is mainly made up of UHM polyethylene, metal or ceramic material. Any combination of these materials has its strengths and weaknesses. Table 2 demonstrates the positive and negative aspects of using these materials:

Hip prosthesis may face the problem of loosening the main reason for this is wear and tear of the material. Wear, reduces the lifetime of the prosthesis, and leads to the formation of destructive debris. Banchet et al. (2007) have carried out tribological tests with different couples (metallic alloys/UHMWPE, ceramics/UHMWPE and ceramics/ceramics) and have compared their performance in terms of friction and wear scars morphology. The results show a lower friction coefficient in the case of ceramics/ceramics couples than in the case of metallic alloys/UHMWPE couples. Wear surfaces were also studied by the use of profilometry and electron microscopy. The wear of UHMWPE is very low when in contact with ceramics, low with Co–Cr alloy and high with stainless steel. Ceramics/ceramics couples show no wear. But in this case there is an additional risk of brittle fracture of ceramic and the limited availability of options.

3. Existing Artificial Hip Joint Designs on the Market.

There are many suppliers of artificial hip joints and the related biomedical equipment. The most popular suppliers include Stryker, DePuy, Smith & Nephew and Zimmer. The National Joint Registry (NJR) has been gathering all statistics related to joint replacements in UK. Everything from the type of prosthesis, the type and number of operations, patient data, and provider type is recorded. The following tables are extracted from the 6th annual report of NJR where the different brands of prosthesis are sorted in terms of number of components used in the hip procedures. The most used cemented and cementless stem brands for hip procedures, including the key benefits are described in Table 3- Table 6.

	Strength	Risk
Metal on Poly	Toughness	Extreme Wear
Ceramic on Poly	Reduced Wear Abrasion Resistance Low Friction	Fracture Risk Fewer Sizes
Metal On Metal	Reduced Wear Head Size Options Toughness	High Ion Levels Less Liner Options Sensitive to Abrasion
Ceramic on Ceramic	Reduced Wear Abrasion Resistance Low Friction	Fracture Risk Limited Options Revision Challenges

Table2. Strength and Risk of Different Material Combination of Acetabular Cup and Lin

Manufacture	Brand	Total components	
		31703	%
Stryker	EXETER V40	19103	60%
Zimmer	CPT	2965	9%
Depuy	CHARNLEY CEMENTED STEM	2041	6%
Depuy	C-STEM CEMENTED STEM	1464	5%
Depuy	C-STEM AMT CEMENTED STEM	949	3%
Biomet	STANMORE MODULAR	868	3%
Smith & Nephew	CPS-PLUS	705	2%

Table3. Cemented Stem Brands during 2008 for Primary Hip Replacements (NJR, 2008).

	• Highly-polished surface designed to reduce friction • Collarless neck helps to facilitate adjustments • Robust choice of size ranges and offsets • Six offset options for every anatomy • Innovative, hollow PMMA centralizer

Table4. Reviewing of EXETER, The Most Commonly Used Cemented Stem Brand.

Manufacture	Brand	Total components	
		26905	%
Depuy	CORAIL	12278	46%
Joint Replacement Instrumentation	FURLONG HAC	3616	14%
Stryker	ACCOLADE	2433	9%
Biomet	TAPERLOC CEMENTLESS STEM	1462	5%
Smith & Nephew	SL-PLUS CEMENTLESS STEM	1450	5%
Zimmer	CLS CEMENTLESS STEM	872	3%
Smith & Nephew	SYNERGY CEMENTLESS STEM	681	3%

Table5. Cementless Stem Brands during 2008 for Primary Hip Replacements (NJR, 2008).

	- The horizontal slits prevent migration. - Hydroxyapatite (HA) stem coating promotes bone tissue growth to hold the prosthesis in place. - Tapered distal end avoids blockages.

Table6. Reviewing of CORAIL, The Most Commonly Used Cementless Stem Brand.

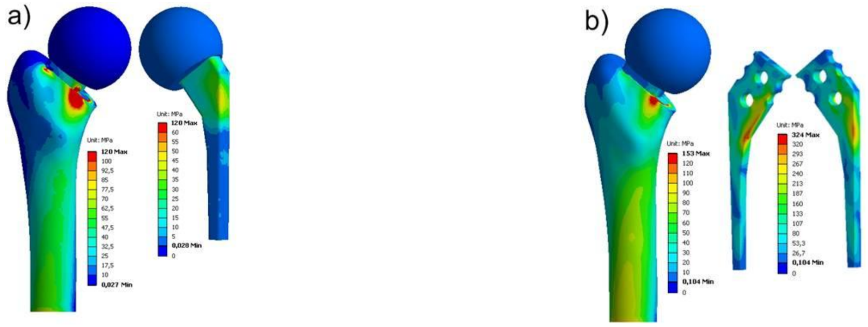

Figure 4. Equivalent von Mises stress distribution. a) Non-Reinforced Spacer at F_R = 3000 N; b) Endoskeleton Including Spacer at F_R = 5000N (Thielen et al., 2009)

4. Design optimisation of hip joints.

One may question the reliability of FEA (finite element analysis). In this regard, Stolk et al. (2002) have corroborated that Finite element and experimental models of cemented hip joint reconstructions can produce similar bone and cement strains in pre-clinical tests. They have compared the results of FEA and experimental models. The objective of overall agreement within 10% was achieved, indicating that FE models were successfully validated. Hence the prerequisite for accurately predicting long-term failure has been satisfied.

Many designs have been developed to improve stress, strain, wear and fatigue life of hip implants. To design a prosthesis of higher durability the natural processes occurring in bone has to be taken into consideration. Pawlikowski et al. (2003) designed a hip joint prosthesis through the acquisition of different steps of CT data, Geometrical modeling of femur, prosthesis design and the numerical analyses of the bone-implant systems helps to finally decide which one of the three designed prostheses is the most appropriate for the patient. Latham and Goswami, (2004) studied the effect of geometric parameters on the development of stress in hip implants. The parameters include: head diameter, neck diameter, and neck angle. In particular it is shown that as the head diameter increases, the stress at a given location reduces. However, as the surface area from increased head diameter increases, the wear rate also increases.

Darwish and Al-Samhan (2009) conducted a parametric study that comprises the parameters affecting the strength of hip-joint cement fixation (offset distance and ball

diameter). They recommend offset distance (3-6 mm) and ball sizes (34 and 50 mm) for maximum cement strength. Matsoukas and Kim (2009) performed the design optimisation of a total hip prosthesis for wear reduction. The accumulation of wear debris can lead to osteolysis and the degradation of bone surrounding the implant components. Bennett and Goswami (2008) carried out CAD FEA on six hip stem designs to come up with a hip stem that has a low stress, *displacement and wear at a very high fatigue lif*e.
On the effect of different factors on design optimisation, Nicolella et al.**(**2005) investigated the effect of three-dimensional prosthesis shape optimisation on the probabilistic response and failure probability of a cemented hip prosthesis system. It is shown that probability sensitivity factors indicate that the uncertainty in the joint loading, cement strength, and implant–cement interface strength have the greatest effect on the computed probability of failure (Figure 4).

The main aim of this project is to develop optimum artificial hip joints with new/ improved design features which can address the following requirements:

- To prevent the risk of dislocation in the hip joints
- To be more resistant to damage and failure by suitably adjusting the strength and stiffness in the implant
- To include design features to make it easier for the surgeons to adjust/ tailor make the implant- more surgeon friendly design
- The improved design should potentially remove the risk of further painful experience, by presenting a completely new design of hip joint.

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