DESIGN AND STRESS ANALYSIS OF ARTIFICIAL HIP JOINT

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ABSTRACT

Artificial hip joint, either as a partial or a total replacement, has become a widely accepted solution for natural hip joint damages. To function as a replacement of a natural joint, the artificial one must fulfill the requirements of biocompatibility, stability and mobility. This study was focused on the 3D geometrical design of a total hip joint replacement and finite element analysis to evaluate the mobility and stability of the artificial joint. First, three dimensional model was built and components were assembled. Then, assembly analysis was used to detect geometrical collision during relative movement. Finally, the geometry of joint replacement components was optimized by carrying out finite element analysis for static and dynamic loadings. Results depicted that the joint mobility of hip joint replacement represented by the range of motion, was not equal to the natural one. However the range of motion of the artificial joint was still satisfactory for daily activity. Finite element analysis results indicated that the strength of hip joint replacement was sufficient which is indicated by the value of the factor of safety. The most critical areas were the neck of the femoral stem and the doom of the cup inlay. From the Finite element analysis (FEA) results, it was also predicted that wear failure tend to occur in the upper periphery of the cup inlay.

KEYWORDS*: Artificial hip joint, Design optimization, Finite element analysis*

1.0 INTRODUCTION

Relative movements of human body are enabled due to the existence of joints which connect bones. However, diseases and injuries may cause severe joint damages. Nowadays, joint replacements, either as total or partial, are widely accepted treatment for damaged joint in many hospitals and they have become a standard procedure in many countries. In the US, the number of surgery procedures to implant

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artificial hip joint is now about 200,000 cases per year and globally the number is still growing due to the increase of life expectancy and obesity cases (Sáenz de Tejada, et al., 2010).

Hip joint is a ball and socket type of joint. The joint connects the femoral bone which has a round head and the acetabulum of the pelvic bone which has a cup shape. This type of joint allows full rotation on one axis as well as flexing and extending.

As a replacement, a joint implant must fulfill stability and mobility requirements to function well in daily activities, therefore artificial hip joint must be carefully designed. This paper was focused on the application of CAD/CAE principles to obtain optimum geometry of a hip joint implant. Finite element analysis (FEA) was carried out, according load human body loadings, to guarantee a sufficient safety.

Beside of geometrical factors, components of hip joint implant are made from materials with far different strength. Therefore, assembly method and minimum thickness of the components must be carefully determined to avoid failures. Failure is crucial in artificial joint because it is implanted in the human body and it is expected to be long term to minimize repeating surgeries.

2.0 DESIGN CONSIDERATION OF HIP JOINT REPLACEMENT

2.1. Components of natural and artificial hip joint

A good joint construction stipulates stability and mobility. In a natural human joint, stability is provided by several ligaments, stretchy fibrous connective tissues, lying around and inside the joint. Joint mobility is enabled through a low friction sliding movement between bone surfaces. The bone surface is covered by a smooth layer of cartilage which is naturally lubricated by synovial fluid.

Beside of low friction, cartilage layer and synovial fluid in human hip joint serve also as damping mechanism when the joint is subjected to impact loading, such as during jumping or running. This joint construction is ideal for high loading condition such as lower extremities joints. Figure 1 gives an illustration of the human hip joint anatomy.

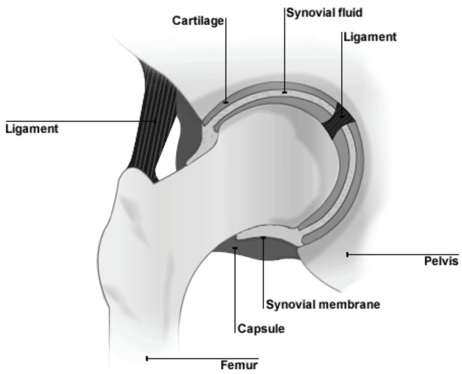


Figure 1. The anatomy of human hip joint (BBC, 2013)

In a hip joint implant, the femoral head bone was replaced by a ball made from metal or ceramic fixed on a metal rod. The rod was designed to have a curve angle of 135°, which was equal to the curve angle of a human natural femoral bone. This metal rod was then implanted in the shaft of the femoral (thigh) bone. A socket made from metal or ceramic was fixed into the acetabulum of the pelvic bone by using cement or screws. An inlay made from soft polymer was inserted in the inner part of the socket to replace the cartilage. A combination of metal-soft polymer provided sliding friction without lubrication which was called self-lubricating contact. The polymer inlay functioned also as a damping during body movement. Figure 2 shows the hip joint replacement with its parts.

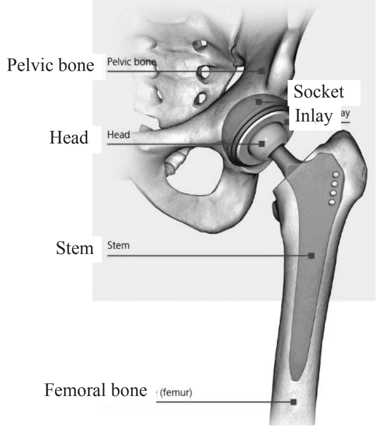


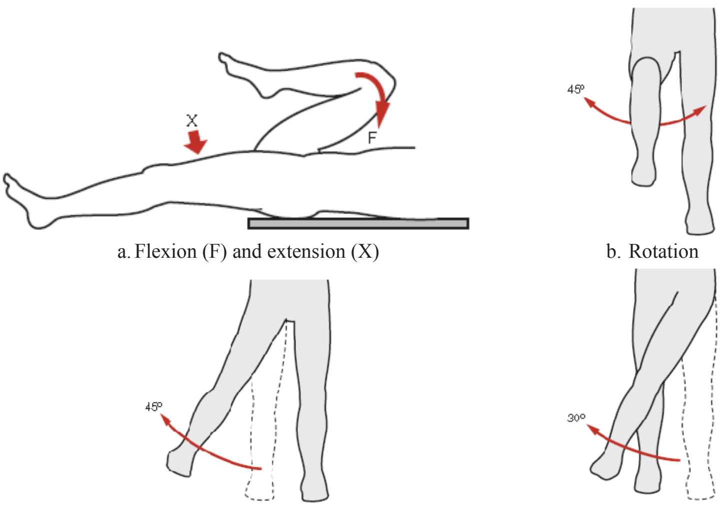
Figure 2. Main parts of hip joint implant
(Mathys Orthopädie GmbH, 2008)

2.2. Mobility and stability of hip joint

2.2.1. Mobility

The mobility of human joint is indicated by the relative motion between bones connected by the joint. This relative motion depends on the contact between bones and also the maximum strains of tissues surrounding the joint. If a natural joint is replaced, the joint replacement should be able to achieve the minimum movement of the natural one. The types of joint movement are flexion, extension, abduction, adduction and rotation. Flexion is the movement to bend the joint and extension is to straighten the joint. Abduction is the movement of joint member outward the body axis and adduction is the movement toward the body axis. Rotation is the movement of joint member around its center.

Figure 3 show the normal range of motion (ROM) of a human hip joint. The maximum angle of flexion movement was 125^o illustrated by bending the right leg forward. The maximum angle of extension was 30^o illustrated by pushing the left leg downward. The limit of rotation angle was 45^o, the maximum abduction angle was 45^o and the maximum adduction angle was 30^o obtained by crossing a leg in front of another.



a. Flexion (F) and extension (X) b. Rotation

c. Abduction d. Adduction

Figure 3. Illustration of hip joint mobility (Thompson & Floyd, 2008)

2.2.2. Stability

Stability in joint is defined by its ability to maintain position of the members during body movement. A stable joint manages to perform movement in its range of motion while carrying load. From biomechanics point of view, hip joint is one of lower extremities parts those bear high load. Mostly, hip joint is subjected to moment loading, except for rotation motion, the load is torsion. As moment and torsion loads depend on the distance or radius from center of axis, the longer the distance the higher the load on the joint.

During normal body movements, such as: walking, running, stair climbing, the load on a hip joint was about 2.5 to 3.0 times of the body weight. While running, the joint load might reach 6 times of the body weight because legs position during running was farther from joint center (Heller, et al., 2005).

Figure 4 below depicts the loading on a hip joint according to Noble (Noble, 1999). Body weight W worked on the centroid of human body was transferred to the hip bone by the ligament and results abductor force FA. FA was produced due the tissue contraction of the ligament positioning on the shoulder part of femoral (thigh) bone. From figure 4, it can be seen that the femoral bone was subjected to bending moment and the neck part of the femoral were the critical area due to stress concentration.

The acetabulum of the hip bone contacted with the head of thigh bone and it caused a normal force FR in the interface. As a consequence, friction force occurred during body movement and wear failure might take place if lubrication was not sufficient. The abductor force F_A and reaction force F_R were expressed as:

$$F_A = \frac{5}{6} W \left(\frac{L}{r} \right) \tag{1}$$

$$F_R = \frac{5}{6} W \sqrt{725 + 5 \cos A} \tag{2}$$

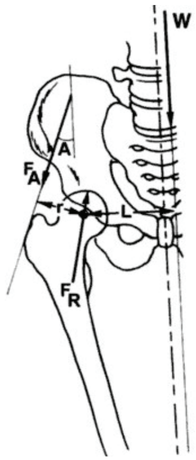


Figure 4. Loadings on hip joint (Noble, 1999)

3.0 3D GEOMETRICAL MODEL OF JOINT REPLACEMENT

3.1. Geometry and material

Based on hip anatomy and the average body size of the human population, the geometrical criteria for hip joint replacement are represented in the Table 1. The values on the table were summarized from ASTM standard (ASTM, 2005).

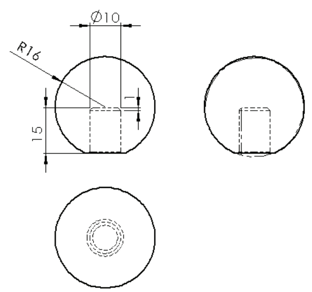
Table 1. Geometrical criteria of artificial hip joint

Criteria	Value
Length of femoral stem	1500 mm
Neck length of femoral stem	20-30 mm (adjustable)
Neck shaft angle of femoral stem	135^o
Diameter of femoral head	30-40 mm (adjustable)
Diameter of acetabular socket	25-30 mm
Range of motion between head socket	$45\text{-}50^o$
Materials	biocompatible

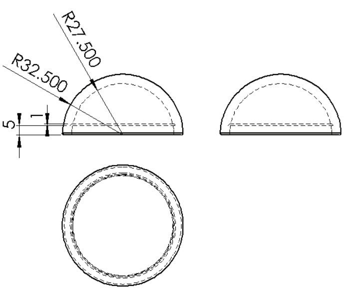
Using the above criteria, 3D geometrical model of artificial hip joint were divided into 4 main parts, namely: femoral stem, femoral head, acetabular socket and cup inlay. Figure 5 shows 3D model and dimension of the joint replacement in details.

Femoral stem, femoral head and acetabular socket were made from Titanium alloy Ti6Al4V which was a biocompatible material. Titanium ions were non-toxic and it has an excellent corrosion resistance in general environment and in human body fluids (Oshida, 2007). From mechanics point of view, Titanium had a high ratio of strength to weight and a very good ductility as well.

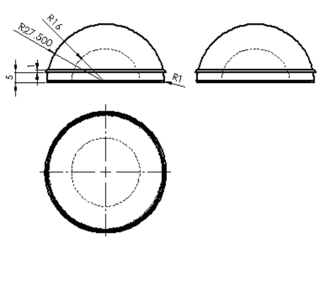
The cup inlay was made from ultra-high molecular weight polyethylene (UHMWPE) which had much higher ultimate strength, ductility and toughness than ordinary polyethylene. UHMWPE was also biocompatible material due to its inertness and its wear resistance. Combination of Titanium-UHMWPE has self-lubricating contact properties with a very low coefficient of friction (Xiong, Gao, & Jin, 2007).



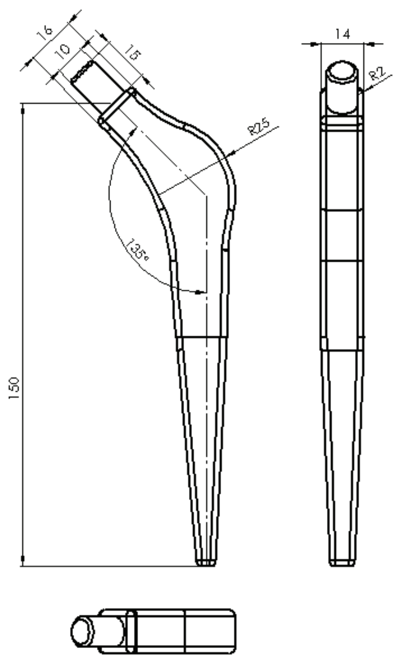
a. Femoral head



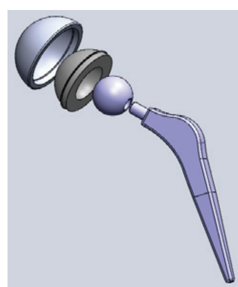
b. Acetabular socket



c. Cup inlay



d. Femoral stem



e. Assembly of parts

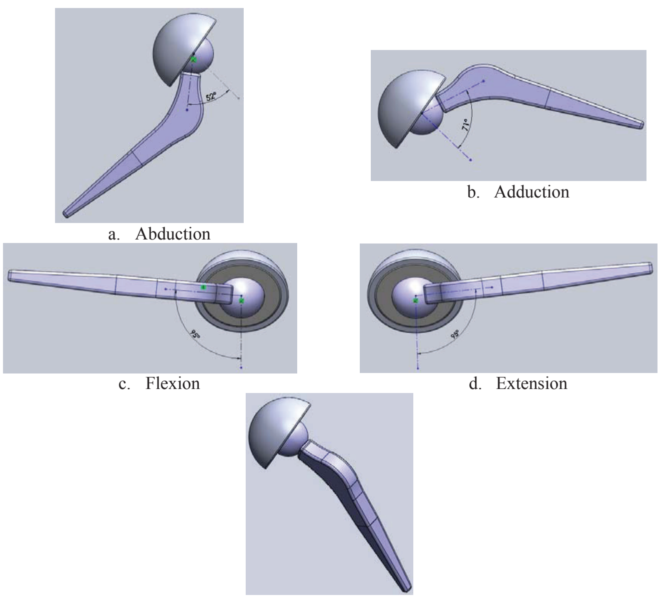
Figure 5. Main parts and dimension of the 3D model of hip joint replacement

3.1. Assembly model and relative movement

Acetabular socket and cup inlay were assembled using interference fit, so that there was no relative movement. Femoral head and its stem were assembled using transition fit to enable adjustment according to the body size of the patient. Relative movement occurred only between the femoral head and the socket.

In assembly modeling, the acetabular socket was used as reference part. Relative position of other parts was defined with the reference part. For instance, the surface of femoral head was defined as coincident with the inner surface of the cup inlay; therefor the two surfaces were always in contact. The neck of the femoral stem were attached to the hole of the femoral head using coincident and concentric definitions, thus not only that the two surfaces were always in contact but the neck and the head hole shared similar axis.

Simulation of relative movements of the assembly model of the hip joint implant was carried out without the constraint of ligament tissues or muscles. A relative movement between the parts was constrained only by geometrical collision as seen in Figure 6. The ROM of the assembly model was then summarized in Table 2.



a. Abduction
b. Adduction
c. Flexion
d. Extension
e. Rotation

Figure 6. Relative movement of the assembly model of artificial hip joint

Table 2. Range of motion of assembly model

Type of Movement	ROM
Adduction	Max. 52^o
Abduction	Max. 71^o
Flexion	Max. 95^o
Extension	Max. 92^o
Rotation	360^o

From the assembly model, it can be seen that the mobility of hip joint implant was lower than the natural one. For flexion movement, the natural joint normally was able to achieve 125^o; meanwhile hip joint implant achieved only 95^o. The angle difference is significant. For abduction and adduction, there is no significant difference, where the ROM of natural one was 45^o, but the implant managed to move 52^o without ligaments and muscles. The ROM for flexion and extension could be increased, however this will reduce the depth of the socket or the contact interface, consequently the femoral head would be easily dislocated.

4.0 STRESS ANALYSIS ON HIP JOINT REPLACEMENT

Titanium has better mechanical properties than bone. Titanium has higher strength and ductility, however Titanium has much higher density and much lower damping properties. Therefore, the geometry of hip joint implant should be design carefully to optimize the weight and the strength. In this paper, stress analysis using finite element method was focused on critical areas namely the neck and shoulder of the femoral stem and the soft polymer inlay.

4.1. Material model, boundary condition and constraints

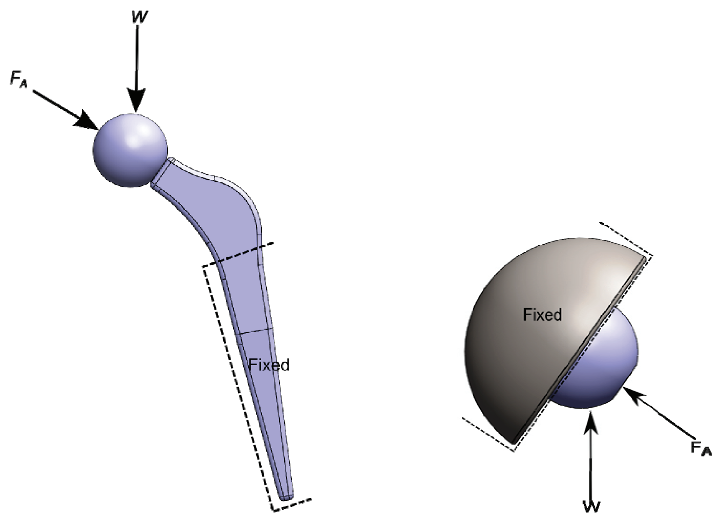
FEA is basically dividing a continuum into small discrete elements to enable unproblematic calculation of the continuum responds to external loads. The external loads can be temperature, force, electrical potential, magnetic fields and so on. When external loads are applied to the continuum, responds on each discrete element are calculated and then solutions from all elements are combined into a global solution or solution of the continuum.

In this study the external loads were mechanical forces and the element respond was displacements. The displacements relate to the external loads through material constitutive equation or material model. For this analysis, an elastic isotropic model was chosen as material model. As a hip joint replacement was expected to bear a load below its elastic limit, elastic isotropic model was considered suitable for both Titanium Ti6Al4V and UHMWPE parts.

Boundary conditions in FEA represent the working environment of the continuum. In this analysis, two boundary conditions were defined, namely the external mechanical force and sliding surface contact. When FEA was carried out for a multipart structure, the surface contact between parts should be defined. The contact could be frictionless, sliding friction, bonded contact or penetrated contact.

To evaluate the safe diameter of the stem neck and the safe dimensions of stem shoulder, the hip joint was subjected to load defined as a uniform force working on the surface of the element. The abductor load FA was set 3433.5 N which was equal to 5 times normal weight of eastern Asia population. The mean adult weight of eastern Asian was 70 kg. The abductor force was applied parallel to the axis of the neck femoral stem. The body weight W was also applied as the second external force. The stem was assumed to be fixed in the thigh bone, so that all the nodes in the fixed areas were constrained to displace in all directions. The boundary conditions and constraints can be seen in Figure 7a.

To evaluate the thickness of the cup inlay, the acetabular socket was assumed to be fixed into the pelvic bone. Inlay and socket was defined to have a bonded contact only in slot surface. The sliding contact between femoral head and cup inlay was defined with relatively low coefficient friction i.e. 0.2. The coefficient of friction might be much lower considering the existence of synovial fluid as joint natural lubricant; however this analysis set the value of friction coefficient for general contact between metal and polyethylene. Figure 7b shows the boundary condition and constraints given to the UHMWPE inlay.



a. Forces and constraint for femoral stem b. Forces and constraints for socket inlay

Figure 7. Boundary conditions and constraints

4.2. Analysis Results and Discussion

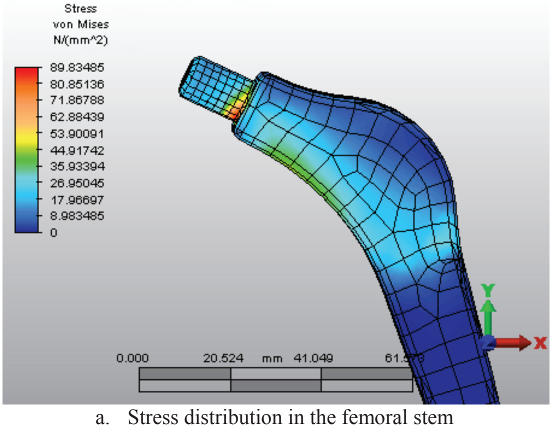
The FEA was carried out for multi-body condition. As the analysis was focus on the femoral stem and cup inlay, this paper shows analysis results only for the two parts. Some results are presented in Figure 8.

From the stress distribution in Figure 8a, it can be seen that the neck of the stem was the most critical area. The effective stress (Von Misses) in neck area could reach 89.93 MPa. Beside the neck, the lower part of the shoulder was also critical area. The external load caused high bending stress combining with compression in these areas. Consequently the diameter of the neck and the cross section of the shoulder should be made bigger. Using the dimension in Figure 5, the minimum factor of safety in the neck area was 10.3 and it was considered sufficient for the joint to bear dynamic loading.

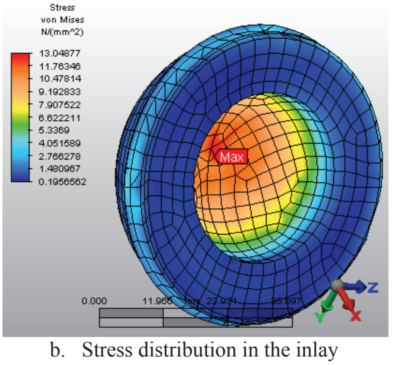
As shows in Figure 8b, high stress and strain occurred in the inside the inlay in the doom area. From this result, a ductile failure was predicted to occur in the doom area. The highest effective stress was 13.05 MPa and the lowest factor of safety was 1.9. This value was relatively low for dynamic loading, however it was considered sufficient since the stress was compression.

FEA results indicated the highest contact force occurred in the upper periphery of the cup. As high contact force indicated high interaction with another surface, friction was predicted to occur in this area.

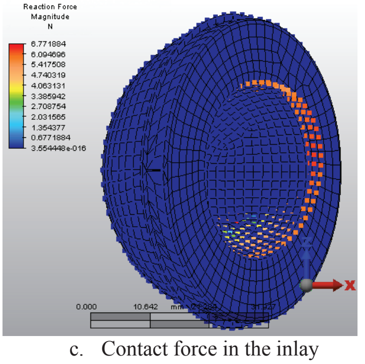
Experimental studies from Mattei (Mattei, Di Puccio, Piccigallo, & Ciulli, 2011) and Wilches (Wilches, Uribe, & Toro, 2008) reported the wear failure in the upper periphery of the cup inlay. Wear failure in the UHMWPE created fine particles released in the human body system and it might cause many complications.



a. Stress distribution in the femoral stem



b. Stress distribution in the inlay



c. Contact force in the inlay

Figure 8. Finite element analysis (FEA) results

5.0 CONCLUSION

From the analysis, it can be concluded:

1. Mechanical functions of natural hip joint could be replaced by an artificial one made from biocompatible materials. The joint made from Titanium alloy and UHMWPE fulfilled the criteria of mobility and stability.
2. The mobility of a hip joint replacement represented by range of motion was not equal to the natural joint. The artificial hip joint had lower ROM in flexion and extension movements, but it had higher ROM in abduction and adduction. This was caused by

the geometrical limitation to compromise ROM and dislocation of the femoral head.

3. Stability of the hip joint replacement represented by its ability to bear load was very good, because Titanium had higher strength and ductility than human bone. The neck of the femoral stem and the shoulder were critical areas, therefore the cross section of these areas should be carefully determined.
4. Cup inlay was the most critical part because UHMWPE had much lower mechanical properties than Titanium. The factor of safety of the inlay was the lowest at the doom area; consequently it had the highest tendency to ductile failure. The contact force in the upper periphery was the highest, thus wear failure was predicted to occur in this area.

6.0 REFERENCES

ASTM. (2005). ASTM Standard F2033-05. *Specification for total hip joint prosthesis and hip endoprosthesis bearing surfaces made of metallic,* ceramic, and polymeric materials. West Conshohocken, PA, USA.: ASTM International.

BBC. (2013, March 01). *BBC Standars Grade Bitesize. Retrieved from Biology* - The body in action - Movement : www.bbc.co.uk

Heller, M., Bergmann, G., Kassi, J., Claes, L., Haas, N., & Duda, G. (2005). Determination of muscle loading at the hip joint for use in pre-clinical testing. *Journal of Biomechanics, 38*(5), 1155-1163.

Mathys Orthopädie GmbH. (2008). Patient Information Broschure. *The artificial hip joint.* Bettlach, Switzerland: Mathys Ltd Bettlach.

Mattei, L., Di Puccio, F., Piccigallo, B., & Ciulli, E. (2011). Lubrication and wear modelling of artificial hip joints: A review. *Tribology International, 44*(5), 532-549.

Noble, P. (1999). Biomechanics of revision hip joint replacement. In J. Bono (Ed.), *Revision Total Hip Arthroplasty (*pp. 135-141). New York: Springer-Verlag.

Oshida, Y. (2007). *Bioscience and Bioengineering of Titanium Materials*. Oxford: Elsevier.

Sáenz de Tejada, M., Escobar, A., Herrera, C., Garcia, L., Aizpuru, F., & Sarasqueta, C. (2010). Patient expectations and health-related quality of life ourcomes following total hip joint replacement. *Value in Health, 13*(4), 447-454.

Thompson, C., & Floyd, R. (2008). *Manual of Structural Kinesology,* 13th Edition. Singapore: McGraw-Hill. Singapore: McGraw-Hill.

Wilches, L., Uribe, J., & Toro, A. (2008). Wear of materials used for artificial joints in total hip replacements. *Wear, 265(*1-2), 143-149.

Xiong, D., Gao, Z., & Jin, Z. (2007). Friction and wear properties of UHMWPE against ion implanted Titanium alloy. *Surface & Coatings Technology,* 201, 6847-6850.