Biomechanical Study on Hip and Knee Joint after Unilateral Total Hip Arthroplasty

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Abstract

Finite element analysis was performed using 3-dimensional model to analyze the biomechanical effects on the hip and knee joint after unilateral total hip arthroplasty. Clinical studies have reported that hip and knee osteoarthritis (OA) often occurred on the contralateral (non-implanted) side after unilateral total hip arthroplasty (THA). Both local and systemic stress-shielding occur on the lower extremities when used various material property of THA implants. It demonstrated that the force reaction with unilateral THA surgery was carried more in ipsilateral side (implanted side) than contralateral side, while total deformation was higher in contralateral side and the maximum stress value was higher on contralateral side of femoral condyles than ipsilateral side.

Keywords: *Total Hip Arthroplasty (THA), Finite Element Method (FEM), Osteaarthritis (OA)*

1. Introduction

In the United States, hip OA occurs about 5% of the population over the age of 60 years and more than 400,000 primary hip and knee athroplasties are performed each year, of which cost is estimated to exceed US$ 10 billion[1,2]. Total hip arthroplasty is a common surgical procedure for the treatment of hip osteoarthritis[3]. THA is highly successful operation performed hundreds of thousands of times worldwide each year and it provides patients with complete pain relief and improved hip functions [4,5]. However, recent studies have reported progression of hip OA might be related to the progression of knee OA [6-8]. Shakoor *et al.*, reported that among patients whose initial THA was followed by total knee arthroplasty (TKA), 71% underwent TKA on the contralateral side[9]. Study also demonstrated that using gait analysis, medial compartment load of the knee was significantly higher in the contralateral knee compared to the treated side at 1-2 years after successful unilateral THA[10]. Umeda *et al.*, [6] performed radiographic evaluation of the knee OA after THA. They reported that 33% of test subjects showed progression of medial tibiofemoral OA on the contralateral side, while only 10% showed progression on the THA side. They asserted that the resistance to OA progression on the ipsilateral side might be caused by the lower offset and resultant lateral shift in mechanical axes.

Purpose of this study is to analyze and verify the previous clinical outcomes related to OA occurrence on the hip and knee joint followed by primary THA by utilizing 3-dimensional (3D) static finite element method. Stress and load distribution on both sides of hip and knee joints were examined in the static situation and the total flexibility on the lower extremities were also considered to see the effect of stress transfer to the opposite side.

2. Material and Methods

Subject specific 3-dimensional finite element model of lower extremities of a man 47 years old and 176 cm tall, including iliac crest, sacrum, right and left femurs and tibias was generated from computed tomography (CT) scans provided by Korea Institute of Science and Technology Information (KISTI) as shown in Figure 1. Left femur was chosen to be implanted with cobalt chrome alloy (Co-Cr) stem and head, UHMWPE acetabular cup. The stem and acetabular cup models were created with commercial software (Pro Engineer, 5.0) using the specifications from previous studies [11, 12]. The final model including the bone and the implant consisted of 79,965 nodes and 42,575elements. ANSYS 13.0 was used for analysis.

Boundary conditions were set to assume the static and stand still position. Proximal part of tibia was set as the fixed support and some surfaces where are anatomically attached by muscles such as adductor brevis, adductor longus, and cracilis were set to have zero rotation in all axes, permitting translation to all 3 axes. Nachemson performed in-vivo measurement on the lumbar spine of 70kg male and reported that the approximate axial load on the L3 was 500N in standing at ease case[13]. Therefore, the loading force of 500 N was applied on sacrum as shown in Figure 1. Two material constants (elastic modulus and poisson's ratio) for typical implant materials were obtained from other literatures and some material properties (as denoted by N###) are arbitrarily created to see the effect of modulus on stress distribution as shown in Table 1 [14-16].

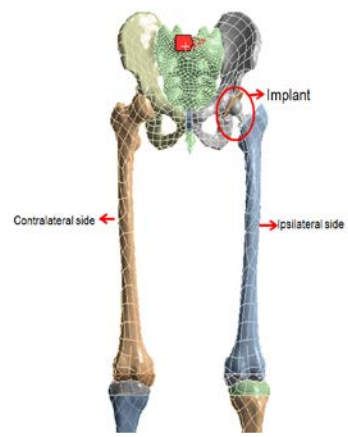


Figure 1. 3D Finite Element Model including Iliac Crest, Sacrum, Femur, Tibia and Total Hip Implant

Table 1. Material Property used in this Simulation

	Elastic Modulus	Poisson's Ratio
Cortical Bone	17.3GPa	0.29
Cancellous Bone	1GPa	0.29
Cartilage	0.013GPa	0.49
Cobalt-Chrome Alloy	200GPa	0.3
Ti-6Al-4V	105GPa	0.3
Low Modulus Ti	42GPa	0.3
PEEK	20GPa	0.4
N180*	180GPa	0.3
N160*	160GPa	0.3
N140*	140GPa	0.3
N120*	120GPa	0.3
N80*	80GPa	0.3
N65*	65GPa	0.3
UHMWPE	1.4GPa	0.46

3. Results

Simulation result showed that when Co-Cr implant was used, force reaction on the ipsilateral (implanted) side was 269N and contralateral (non-implanted) side was 233N as shown in Figure 2. Total force reaction was 15% higher on the ipsilateral side compared to that of the contralateral side. As elastic modulus increased, force reaction increased on the ipsilateral side and decreased on the contralateral side.

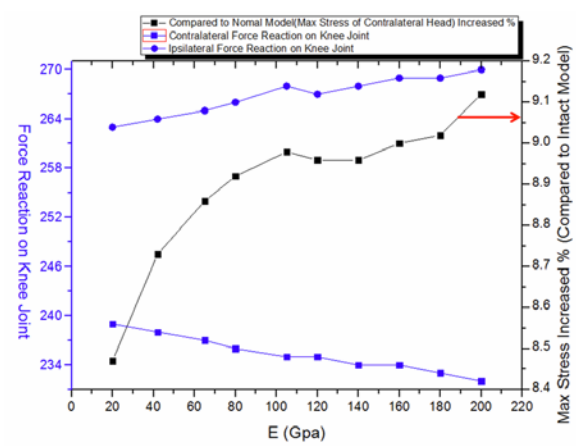


Figure 2. Force Reaction of Knee Joint and Max. Stress of Femoral Head Increased %(Compared Intact Model)

Interestingly, the result showed that higher stress concentration occurred on the contralateral femoral head and condyles. Maximum equivalent stress value (Von-Mises) was higher for the model with Co-Cr implant when compared to the intact model (w/o implant). As elastic modulus increased, maximum stress on the contralateral head also increased whereas the stress on contralateral femoral condyles decreased as shown in Figure 2 and 3. In the contralateral femoral condyle, the maximum stress was developed on the medial part. The maximum stress values were 0.24MPa and 0.14MPa respectively on the medial part and lateral part with Co-Cr implant and stress level was higher on the medial part on the whole as shown in Figure 4.

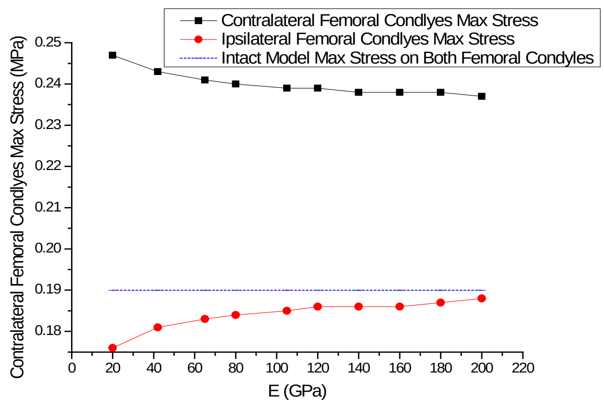


Figure 3. Max Stress of Femoral Condyles

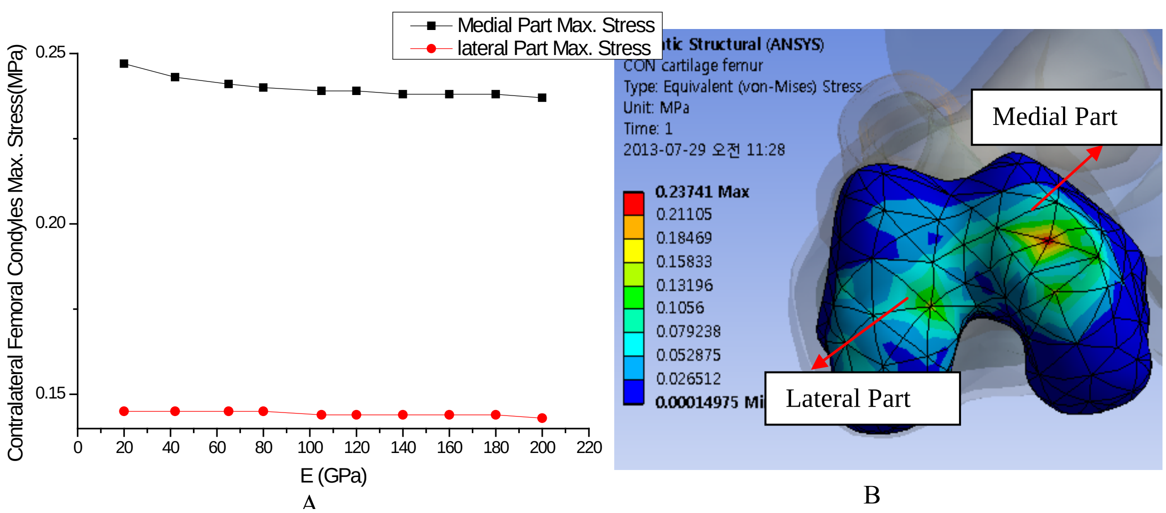
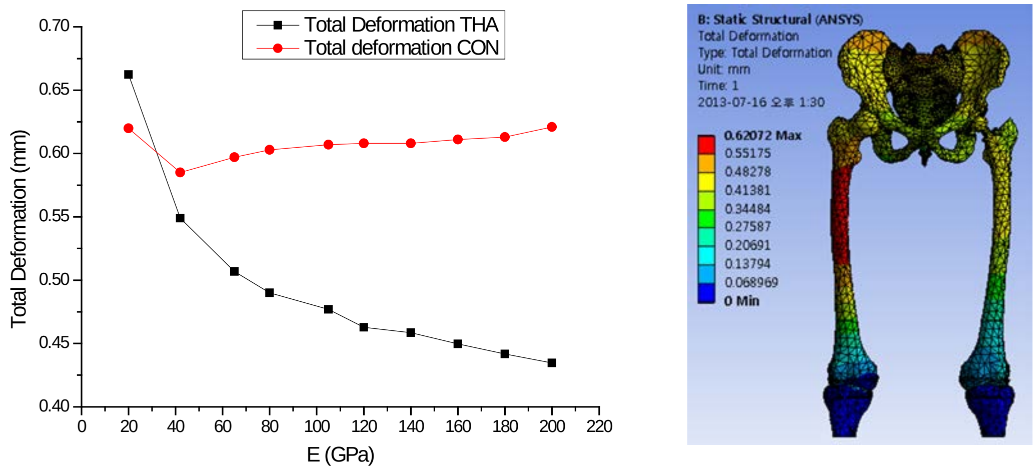


Figure 4. A:Max. Stress Value on the Contralateral Femoral Condyles Medial Part and Lateral Part; B: Max. Stress occuring Medical Position

Maximum total deformation (0.66mm) on the implant occurred when used PEEK implants, whereas the-maximum total deformation (0.62mm) on the contralateral side occurred when used Co-Cr implants. As elastic modulus increased, maximum total deformation increased on the contralateral side and decreased on the implants. But the case of PEEK implant, the maximum total deformation on the contralateral side is similar to used Co-Cr implants case as show in Figure 5.



A B

Figure 5. A: Max. Total Deformation on Implants and Contralateral Side; B: Max. Total Deformation Display on Whole Model

4. Discussions

Natural load distribution on the femur is altered after the THA and the implant will carry a higher portion of the load, which is termed as stress shielding [17, 18]. Finite element analysis result in this study showed that load distribution on the ipsilateral side of Co-Cr hip implant was higher than contralateral side by 15%. The more the implant was stiffer (that is, higher elastic modulus), the more load the ipsilateral side took over than the contralateral side. The contralateral side of Co-Cr hip implant had 8% lower force reaction compared to intact model.

Previous clinical studies, however, showed that the progression of OA after THA was more likely to occur on the opposite side, that is, non-implanted side where the load sharing was lower. Shakoor et al. demonstrated that the OA evolved nonrandomly after the joint was unilaterally replaced, and the contralateral limb showed significantly more progression of OA than the ipsilateral limb[9]. This is an opposite phenomenon to the general concept that increased load predicts the structural progression of OA on the joints.

Interestingly, maximum stress of contralateral femoral head showed increase of 9% and contralateral femoral condyles showed increase of 20% with Co-Cr. This was due to the fact that flexibility tended to be higher on the contralateral side since the elastic modulus of cortical bone was much lower than that of cobalt chrome alloy. The total deformation on the contralateral side increased overally by increasing stiffness or elastic modulus of the implant. Due to bending to the midline of the body, the higher stress concentration was induced on the medial part of the contralateral femoral condyle than the lateral part. This showed a strong tendency to the study by Shakoor *et al.*, which demonstrated OA was developed especially on the medial part of the contralateral side[9].

Recent several studies have reported that anomalous mechanical stress was suspected to be a main cause of progressing OA [19-21]. Simulation result showed that as elastic modulus increased, maximum stress on contralateral femoral condyles decreased slightly. Force reaction on the knee joint showed similar pattern by decreasing on the contralateral side as the elastic modulus increased. This is caused by the rigidity material and difference in force flow. Since the femoral condyle is further away from the implant position, force reaction seems to be the main cause of this phenomenon.

5. Conclusion

Three findings were demonstrated from the simulation results in this study. First, natural load flow in the lower extremities was altered after unilateral total hip arthroplasty, and the implant would carry a higher portion of the load. Second, stress concentration was on the contralateral side, especially on the medial femoral condyle, because the bone and implants had dissimilar flexibility. Third, the total deformation on the contralateral side, and thus maximum stress was affected by elastic modulus of implants. On conclusion, the mechanical effect, especially maximum stress is believed to be closely related to OA after unilateral total hip arthroplasty.

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