Static and Dynamic Load on Hip Contact of Hip Prosthesis and Thai Femoral Bones

K. Chalernpon, P. Aroonjarattham, K. Aroonjarattham

***Abstract*—**Total hip replacement had been one of the most successful operations in hip arthritis surgery. The purpose of this research had been to develop a dynamic hip contact of Thai femoral bone to analyze the stress distribution on the implant and the strain distribution on the bone model under daily activities and compared with the static load simulation. The results showed the different of maximum von Mises stress 0.14 percent under walking and 0.03 percent under climbing stair condition and the different of equivalent total strain 0.52 percent under walking and 0.05 percent under climbing stair condition. The muscular forces should be evaluated with dynamic condition to reduce the maximum von Mises stress and equivalent total strain.

***Keywords*—**Dynamic loading, Static Load, Hip prosthesis, Thai femur, Femoral bone, Finite Element Analysis.

I. Introduction

HUMAN body carries body weight and absorbs shock using hip joint during walking and climbing stair conditions. When the hip joint is worn out or damaged, total hip replacement, which is the most successful operative surgery to help the patient return to their usual lifestyle, is performed. The knowledge of the hip joint force developed by the body weight during dynamic activity could be of interest in the biomechanical study.

The hip prosthesis was divided into two types: cemented and cementless hip prosthesis. The disadvantages of the cemented hip arthroplasty include the femoral loosening and bone loss [1]. To eradicate these shortcomings, the cementless hip prosthesis was then introduced. There were many reports of cementless hip prosthesis revealing the low rates of aseptic, loosening and stability for the bone ingrowth [2]-[8]. The stem of cementless fixation is based on a gradual proximal-to-distal off-loading as a result of the tapered geometry. The tapered design induced an even transfer of stress from the stem to the bone in a proximal-to-distal fashion as show in Fig. 1.

This study aims to evaluate the von Mises stress distribution on the cementless hip prosthesis and the equivalence of total strain distribution on Thai femoral bone under daily activities as walking and climbing stairs conditions by simulating the hip contact, which acted on the femoral head with static and dynamic conditions to compare the effects of different load types on the Thai femur.

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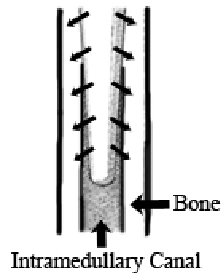

Fig. 1 Weight-bearing force on a tapered stem are off-loading gradually to the bone of the proximal femur

II. Materials and Methods

A. Three- Dimensional Bone Model

The femoral bone was scanned by computerized tomography (CT) scanner (GE LightSpeed VCT, Thailand) from Faculty of Medicine, Burapha University. The CT data imported to ITK-SNAP software to convert the data to the Stereo Lithography (stl) file [9]. The model consisted of cortical and cancellous bone as shown in Fig. 2.

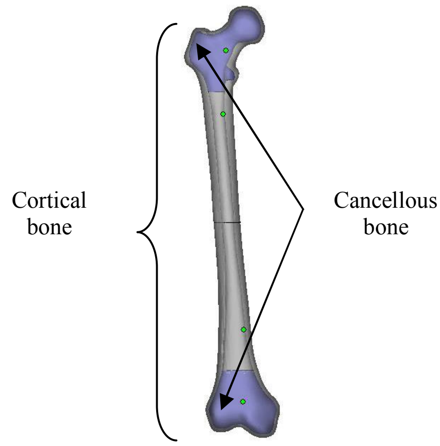

Fig. 2 Three-dimensional Thai femoral bone

B. Virtual Simulation

Along the virtual simulation method in the study, the hip prosthesis was inserted into the neutral alignment with the femoral shaft axis as shown in Fig. 3. The head of the prosthesis was fixed at the same position of the femoral head in order to transfer the load from the proximal part to the distal part.

C. Mesh Generation

Mesh generation in each model were generated by MSC Marc (Version 2010, Mahidol University, Thailand). The four-node tetrahedral element was chosen in this research in order to reduce the calculating time. Ramos and Simones compared experiment mesh element form tetrahedral element with hexahedral element and the result showed that the tetrahedral element form four nodes is similar to the that of the theory [10]. The femur-implant model had a total of 56,557 nodes and 238,796 elements. The femur-implant models are shown in Fig. 4.

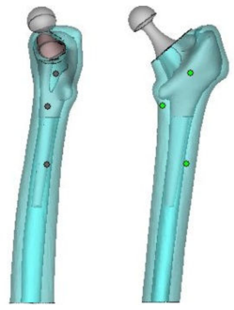

Fig. 3 The position of hip prosthesis inserted in the femoral bone: (a) Medial side and (b) Posterior side

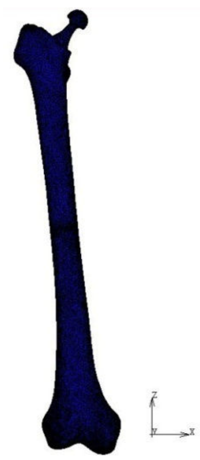

Fig. 4 Mesh model of femur-implant

D.Material Properties

Femoral bone was divided to two parts as cortical bone had elastic modulus at 14,000 MPa and Poisson's ratio at 0.30 and cancellous bone had elastic modulus at 600 MPa and Poisson's ratio at 0.20. Hip prosthesis had elastic modulus at 110,000 MPa and Poisson's ratio at 0.3. All models were assumed to be linear elastic, an isotropic and homogeneous material [11].

E. Boundary Condition

A fully fix at the distal end was used in this study. The body weight acted on the tip of femoral head and muscular force acted on the proximal femur as shown in Fig. 5.

The magnitude of muscular forces is shown in Tables I and II for walking and climbing stairs condition respectively [12]. The hip contact, which transfers load from the upper body to the lower part, was investigated in two conditions: static condition, which was shown in Tables I and II and dynamic condition, which was shown in Figs. 6 and 7.

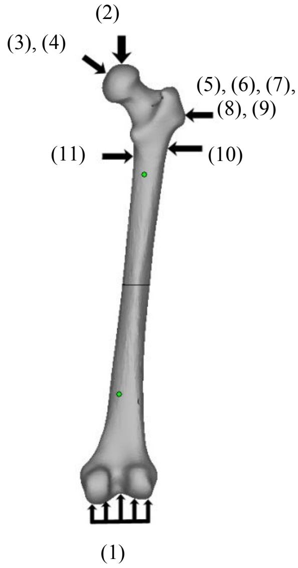

Fig. 5 The position of muscular force act on proximal femur

TABLE I
THE MUSCULAR FORCE ACT ON THE PROXIMAL FEMUR UNDER WALKING CONDITION [12]

Position	Forces	Fx	Fy	Fz
1	Fix displacement	-	-	-
2	Body weight	0	0	-836.0
3	Hip contact	-54.0	-32.8	-229.2
4	Intersegmental resultant	-8.1	-12.8	-78.2
5	Abductor	58.0	4.3	86.5
8	Tensor fascia latae, proximal part	7.2	11.6	13.2
9	Tensor fascia latae, distal part	-0.5	-0.7	-19.0
10	Vastus lateralis	-0.9	18.5	-92.9

TABLE II
THE MUSCULAR FORCE ACT ON THE PROXIMAL FEMUR UNDER CLIMBING STAIR CONDITION [12]

Position	Forces	Fx	Fy	Fz
1	Fix displacement	-	-	-
2	Body weight	0	0	-847
3	Hip contact	-59.3	-60.6	-236.3
4	Intersegmental resultant	-13.0	-28.0	-70.1
5	Abductor	70.1	28.8	84.9
6	Ilio-tibial tract, proximal part	10.5	3.0	12.8
7	Ilio-tibial tract, distal part	-0.5	-0.8	-16.8
8	Tensor fascia latae, proximal part	3.1	4.9	2.9
9	Tensor fascia latae, distal part	-0.2	-0.3	-6.5
10	Vastus lateralis	-2.2	22.4	-135.1
11	Vastus medialis	-8.8	39.6	-267.1

The dynamic loads of hip contact are shown in Figs. 6 and 7 for walking and climbing stairs condition respectively [13].

The contact condition is to determine the correspondence among of MSC fragments. The program was meant to define the relationship of the contact with the 3 characteristics: no contact, touch contact and glue contact condition. The glue contact condition was applied to this research, where the underside hip prosthesis contacts the bone cuts. The glue contact was assumed to replace a rigidly fixed implant with bone ingrowths [14]. Finite element analysis of MSC software was calculated by using micro-motion of force in each node and verifying tangent surface together. In this thesis, iterative of Newton-raphson was used for calculating.

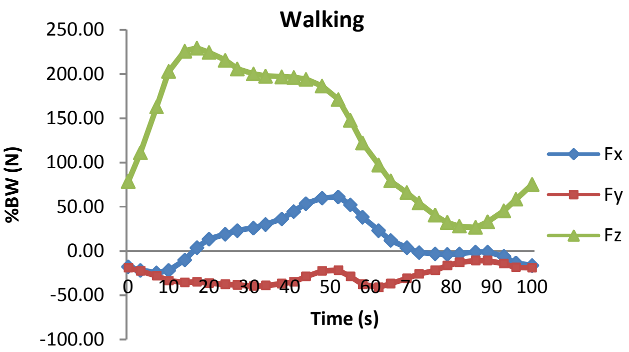

Fig. 6 The hip contact act on x-, y- and z-axis under walking condition

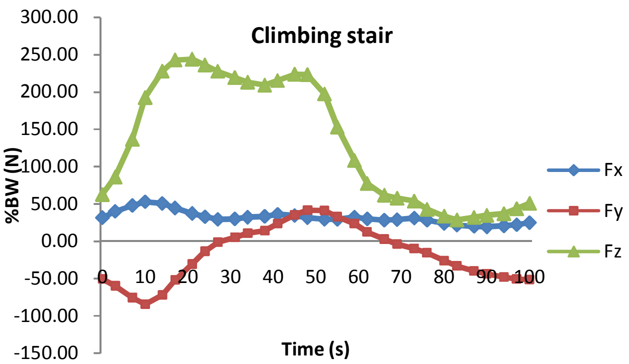

Fig. 7 The hip contact act on x-, y- and z-axis under climbing stair condition

III. Result

The maximum von Mises stresses on hip prosthesis were measured for 4 cases as static walking, static climbing stairs, dynamic walking and dynamic climbing stairs as shown in Table III.

TABLE III
THE MAXIMUM VON MISES STRESS ON HIP PROTHERSIS UNDER FOUR CONDITIONS

Condition	The maximum von Mises stress (MPa)
Static Walking	137.07
Static Climbing Stair	138.87
Dynamic Walking	136.88
Dynamic Climbing Stair	138.83

The stress distributions on the hip prosthesis under static walking and static climbing stair are shown in Fig. 8.

The stress distributions on the hip prosthesis under dynamic walking and dynamic climbing stair at every 10 second are shown in Figs. 9 and 10 respectively.

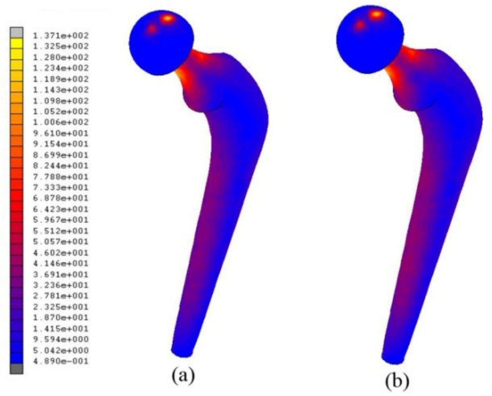

Fig. 8 The stress distribution on hip prosthesis under: (a) static walking and (b) static climbing stair condition

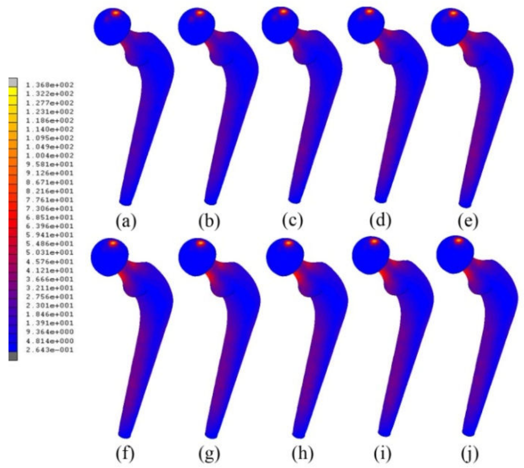

Fig. 9 The stress distribution on hip prosthesis under dynamic walking at every 10 second: (a) 10, (b) 20, (c) 30, (d) 40, (e) 50, (f) 60, (g) 70, (h) 80, (i) 90 and (j) 100 second

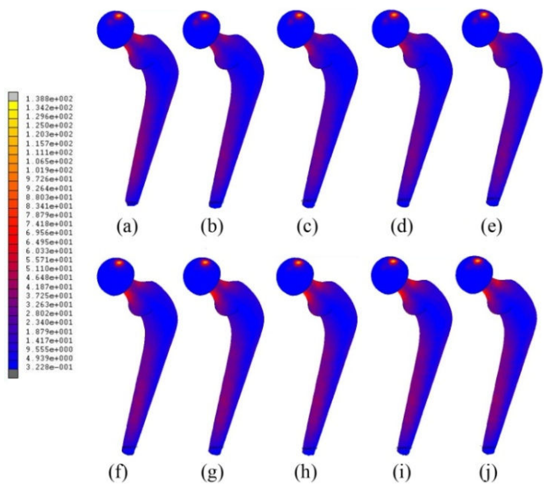

Fig. 10 The stress distribution on hip prosthesis under dynamic climbing stair at every 10 second: (a) 10, (b) 20, (c) 30, (d) 40, (e) 50, (f) 60, (g) 70, (h) 80, (i) 90 and (j) 100 second

IV. Discussion

The stress and strain distribution analysis using the finite element method is widely accepted as a useful technique to evaluate or predict the biomechanical behaviors of orthopedic implants under certain load condition. The muscular load configuration was applied to the biomechanical study of a hip prosthesis when inserted in a Thai femoral bone. The results regarding the stress distribution on the implant and the strain distribution on the femoral bone will be discussed respectively.

A. Stress Distribution on the Implant

The least maximum von Mises stress can reduce the long-term problem of the implant failure [15], [16]. The maximum von Mises stress under static and dynamic conditions did not reach the yield strength of hip prosthesis Yield strength of titanium alloy is 850 MPa [17], which shows that the hip prosthesis is safe for static and dynamic condition of hip contact. The maximum von Mises stress on the hip prosthesis under static condition was higher than dynamic condition 0.14 percent (0.19 MPa) under walking and 0.03 percent (0.04 MPa) under climbing stairs condition.

Considering all muscular forces with dynamic condition, the hip prosthesis's size can be reduced because, with the dynamic condition- the more realistic condition-, the results show even lease maximum von Mises stress than the results with static condition.

B. Strain Distribution on the Femur

The maximum strain distributions on femoral bone, varied by time under dynamic walking and dynamic climbing stairs condition, are shown in Figs. 11 and 12 respectively.

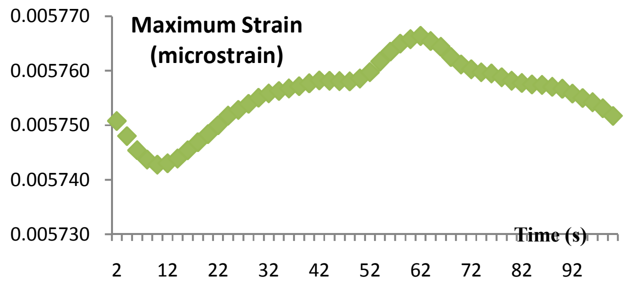

Fig. 11 The maximum strain distribution on femoral bone under dynamic walking condition

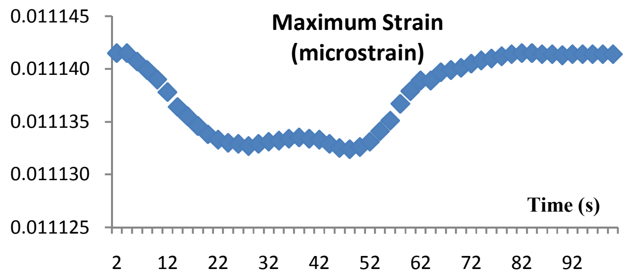

Fig. 12 The maximum strain distribution on femoral bone under dynamic climbing stair condition

The maximum strain distributions on the femoral bone, which was occurred under 4 conditions, are shown in Table IV.

TABLE IV
The Maximum Strain on Femoral Bone under Four Conditions

Condition	The maximum strain (microstrain)
Static Walking	5,782
Static Climbing Stair	11,147
Dynamic Walking	5,752
Dynamic Climbing Stair	11,141

The maximum strain on the bone under static condition was higher than dynamic condition 0.52 percent under walking and 0.05 percent under climbing stair condition.

Normally the fracture of lamellar bone occurs when its mechanical strains attain some 25,000 microstrain [18]. From the results, the patient can put full load on the hip prosthesis.

V. Conclusion

The static condition of hip contact gives nearly similar results to the dynamic condition with the static results showing slightly higher value than the dynamic results. The muscular forces should be evaluated with dynamic condition to reduce the stress and strain distributions on the prosthesis and the femoral bone. The maximum von Mises stress on the hip prosthesis was far from the yield strength of titanium alloy showing that the size hip prosthesis in use is bigger than necessary for Thai femoral bone.

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References

[1] E.J. Hellman, W. N. Capello, and J.R. Feinberg. "Omni fit cementless total hip arthroplasty: a 10-year average follow-up" *Clin Orthop.* 1999 vol. 364, pp.164-174.
[2] M.M. Alexiades, M.R. Clain and M.J. Bronson. "Prospective study of porous coated anatomic total hip arthroplasty" *Clin Orthop*. 1991 vol. 269, pp. 205-208.
[3] B.C. Burkhart, R.B. Bourne and C.H. Rorabeck. "Thigh pain in cementless total hip arthroplasty: a comparison of two systems at 2 years' follow-up" *Orthop Clin North Am.* 1993 vol. 24, pp. 645-653.
[4] P.A. Dowdy, C.H. Rorabeck and R.B. Bourne. "Uncemented total hip arthroplasty in patients 50 years of age or younger" *J. Arthroplasty* 1997 vol. 12, pp. 853-862.
[5] W.C. Head, T.H. Mallory and R.H. Emerson Jr. "The proximal porous coating alternative for primary total hip arthroplasty" *Orthopedics* 1999 vol. 22, pp. 813-815.
[6] T.H. Mallory, W.C. Head and A.V. Lombardi. "Tapered design for the cementless total hip arthroplasty femoral component" *Clin Orthop* 1997 vol. 344, pp. 172-178.
[7] T.H. Mallory, W.C. Head and A.V. Lombardi Jr. "Clinical and radiographic outcome of a cementless, titanium, plasma spray-coated total hip arthroplasty femoral component: justification for continuance of use" *J. Arthroplasty* 1996 vol. 11, pp. 653-660.
[8] B.D. Mulliken, R.B. Bourne and C.H. Rorabeck. "A tapered titanium femoral stem inserted without cement in a total hip arthroplasty: radiographic evaluation and stability" *J. Bone Joint Surg Am* 1996 vol. 78, pp. 1214-1225.

[9] P. Aroonjarattham, K. Aroonjarattham and C. Suvanjumrat. "Effect of mechanical axis on strain distribution after total knee replacement" *Kasetsart J. (Nat. Sci.)* 2014 vol. 48, pp.263-282.
[10] A. Ramos and J.A. Simoes. "Tetrahedral versus hexahedral finite elements in numerical modeling of the proximal femur" *J. Med Eng&Phy* 2006 vol. 28, pp. 916-924.
[11] A. Peraz, A. Mahar, C. Negus, P. Newton, and T.J. Impelluso, "A computational evaluation of the effect of intramedullary nail material properties on the stabilization of simulated femoral shaft fracture" *J. Med Eng & Phys* 2008 vol. 30, pp.755-760.
[12] M.O. Heller, G. Bergman, J.P. Kassi, L. Claes, N.P. Hass and G.N. Duda, "Determination of muscle loading at the hip joint for use in pre-clinical testing," *J. Biomechanics* 2004 vol. 38, pp. 1155-1163.
[13] C. Fabry, S. Herrmann, M. Kaehler, E.D. Klinkenberg, C. Woernle and R. Bader. "Generation of physiological parameter sets for hip joint motions and loads during daily life activities for application in wear simulators of the artificial hip" *Med Eng & Phy* 2013 vol. 35, pp. 131-139.
[14] Z. Paul, B. David, E.G. Allan and P. Marcello. "Notching of the Anterior Femoral Cortex during Total Knee Arthoplasty" *J. Arthroplasty* 2006 vol. 21, pp. 737-743.
[15] D.G. Chess, R.W. Grainger, T. Phillips, Z.D. Zarzour and B.R. Sheppard. "The cementless anatomic medullary locking femoral component: an independent clinical and radiographic assessment" *Can J. Surg* 1996 vol. 39, pp. 388-392.
[16] H. Effenberger, T. Ramsauer, G. Bohm, G. Hilzensauer, U. Dorn and F. Lintner. "Successful hip arthroplasty using cementless titanium implants in rheumatoid arthritis" *Arch Orthop Trauma Surg* 2002 vol. 122, pp. 80-87.
[17] J. Black and G. Hastings. 1998 "Handbook of biomaterials properties" Chapman & Hall, UK.
[18] H.M. Frost. "Bone Mass and the Mechanostat:A Proposal" *The Anatomical Record* 1987 vol. 219, pp. 1-9.

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