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Mechanical Evaluation of Stainless Steel and Titanium Dynamic Hip Screws for Trochanteric Fracture

Supakit Rooppakhun, Nattapon Chantarapanich, Bancha Chernchujit, Banchong Mahaisavariya,
Sedthawatt Sucharitpwatskul, and Kriskrai Sitthiseripratip

Abstract—This study aimed to present the mechanical performance evaluation of the dynamic hip screw (DHS) for trochanteric fracture by means of finite element method. The analyses were performed based on stainless steel and titanium implant material definitions at various stages of bone healing and including implant removal. The assessment of the mechanical performance used two parameters, von Mises stress to evaluate the strength of bone and implant and elastic strain to evaluate fracture stability. The results show several critical aspects of dynamic hip screw for trochanteric fracture stabilization. In the initial stage of bone healing process, partial weight bearing should be applied to avoid the implant failure. In the late stage of bone healing, stainless steel implant should be removed.

***Keywords*—**Trochanteric fracture, Dynamic hip screw (DHS), Finite element analysis.

I. INTRODUCTION

TROCHANTERIC fracture is one of the most common orthopedic injuries found in elderly [1]-[4]. The early treatment of trochanteric fracture is necessary to give anatomical alignment of the fracture [5] otherwise it may lead varus malunion, limb shortening and external rotation of the femur due to posteromedial comminution [1]. Aims of the trochanteric fracture surgery are to stabilize the fracture in reduced position and to provide the early weight-bearing [1] , [5]. Beside trochanteric gamma nail (TGN), dynamic hip screw (DHS) is also a widely accepted fracture fixation to treat the femur fracture in trochanteric region [6]-[8]. The concept of dynamic hip screw is to provide a controlled collapse at the fracture site after the implant is secured to femoral head and femoral shaft [1].

Most of the studies were usually to investigate the mechanical performance of the dynamic hip screw at the early stage of bone healing (just after injury) by means of mechanical testing [7], [9]. During the healing process, the mechanical model for evaluation of the mechanical performance may be difficult to set up. The observations of post-operative mechanical performances are usually accessed by radiographic technique which allow the observation about possibility of implant failure or changing of bone at fracture site [10]. Although it is simple, but accessing mechanical performance evaluation by this method cannot be certain.

This study is aimed to evaluate mechanical performance of the stainless steel and titanium dynamic hip screws by means of finite element method. A three-dimensional finite element model of a proximal femur with a trochanteric fracture, stabilized by 2-hole dynamic hip screw was created to investigate stress distribution exhibits on the implant as well as the fracture stability during walking activity. The evaluations of mechanical performance for dynamic hip screw at various healing stages were also accessed. By this way of study, the stress distributions and fracture stabilities during early stage of healing process until late stage of healing process could be investigated.

II. MATERIALS AND METHODS

All finite element models presented here were constructed based on computed tomography (CT) data. The analyses were performed using MSC Marc/Mentat 2005 finite element software package.

A. Finite Element models

A three-dimensional CAD model of the proximal femur was created from CT data using reverse engineering and medical image processing techniques. The Jessen type-I fracture [11] was created as a 2-mm gap in the trochanteric region. The set of dynamic hip screw employed in this study composed of lag screw, 2-hole dynamic hip plate and screws. The set of dynamic hip screw were also captured their surfaces by means of reverse engineering technique using three-dimensional optical scanner. The obtained surfaces were then converted to three-dimensional CAD models. The set of dynamic hip screw was inserted virtually to the proximal

Rooppakhun S. is with the School of Mechanical Engineering, Institute of Engineering, Suranaree University of Technology, Nakon Ratchasima, Thailand (corresponding author to provide phone: +66-44-224553; fax: +66-44-224613; e-mail: supakit@sut.ac.th).

Chantarapanich N. is with Institute of Biomedical Engineering, Prince of Songkla University, Songkla, Thailand.(e-mail: nattapon.chan@gmail.com)

Chernchujit B. is with Department of Orthopedics, Faculty of Medicine, Thammasat University, Pathumthani, Thailand.(email: bancha61@yahoo.com)

Mahaisavariya B. is with Department of Orthopaedic Surgery and Rehabilitation, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok, Thailand.(email: sibmh@mahidol.ac.th)

Sucharitpwatskul S., and Sitthiseripratip K are with National Metal and Materials Technology Center (MTEC), Pathumthani, Thailand. (e-mail: sedthaws@mtec.or.th, kriskrs@mtec.or.th)

femur model. The lag screw was aligned parallel to femoral neck axis. Later, the dynamic hip plate was also aligned parallel to femoral shaft; the plate was touched to the cortical bone. Finally, the screws were then placed to the screw holes. The three-dimensional models of the proximal femur and implant are illustrated in Fig. 1.

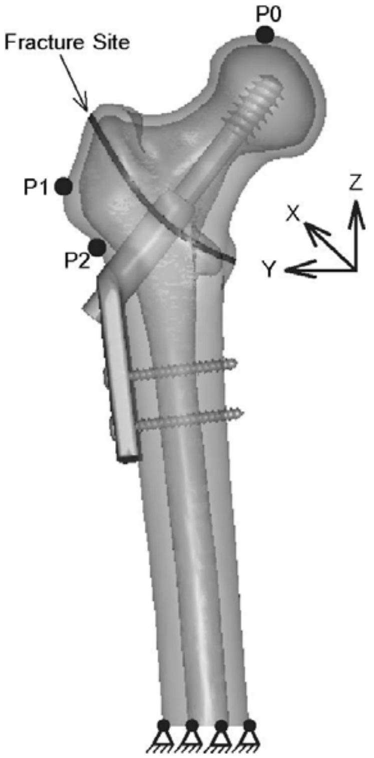

Fig. 1 Three-dimensional model of 2-hole dynamic hip screw stabilized the trochanteric fracture and the boundary conditions.

TABLE I
MATERIAL PROPERTIES USED IN THIS STUDY [12], [13]

Part	Elastic Modulus (MPa) / Poisson's ratio	
	Cortical Bone	Trabecular Bone
Intact Femur		
- Femoral Head	17,000 / 0.30	900 / 0.29
- Femoral Neck	17,000 / 0.30	620 / 0.29
- Femoral Introchanteric Region	17,000 / 0.30	260 / 0.29
- Femoral Shaft	17,000 / 0.30	-
Fracture Site		
- Stage I (Early Stage of Fracture Healing)	3 / 0.4	3 / 0.4
- Stage II (Healing)	100 / 0.29	100 / 0.29
- Stage III (Healing)	260 / 0.29	260 / 0.29
- Stage IV (Intact)	17,000 / 0.30	260 / 0.29
Implant		
- Stainless steel	200,000 / 0.30	
- Titanium	110,000 / 0.33	

Four-node tetrahedral elements based on STL automatic mesh generation technique were used to generate nodes and elements of the proximal femur and the set of dynamic hip screws. Different regions in the model were introduced the definition of different material properties and contact conditions. The femur-implant model had a total of 38,887 nodes and 163,352 elements.

TABLE II
LOADING CONDITION UNDER WALKING ACTIVITY [14]

Force	Magnitude			
	X	Y	Z	Point
Hip contact	274	451	-1,916	P0
Intersegmental Resultant	107	68	-654	P0
Abductor	-36	-485	723	P1
Tensor Fascia Latae (Proximal Part)	-97	-60	110	P1
Tensor Fascia Latae (Distal Part)	6	4	-159	P1
Vatus Lateralis	-154	8	-777	P2

B. Material properties

Linear elastic isotropic material properties were assigned to the finite element model. Different material properties were attributed to different regions of the proximal femur. In each state of healing, the fracture was given the material properties differently. In the early state of healing, the initial connective tissue was a material property of the fracture. During healing process, the material property (elastic modulus) of the fracture was increased proportionally to the time of rehabilitation. The material definition of implant was assigned as stainless steel and titanium. Corresponding elastic constants used in this model were presented in Table I.

C. Boundary conditions

Table II and Fig. 1 present the loading conditions and boundary conditions described by Heller *et al.* [12] which applied to the proximal femur during walking activity. The applied loads also included joint reactions and related muscle forces. The distal end of the proximal femur model was fully fixed.

D. Contact conditions

In order to simplify the analysis, among each of contact bodies were frictionless. All contact bodies related to intact femur were no relative displacement to each other. The lag screw and screws attached to the proximal femur was allowed the relative displacement. The dynamic hip plate was also allowed the relative displacement to lag screw and screws.

III. RESULTS

A. Stress distribution

The risk of the implant failure could be observed by maximum von Mises stress which exhibits on implant. The critical regions were considered to be at the lag screw and screw sets as the high von Mises stress were found. From Table III and Table IV, it can be obviously seen that the stainless steel implant presented higher magnitude of maximum von Mises stress than the titanium implant. For both materials, the von Mises stress on the implant reduced to lower values throughout the healing process. Fig. 2 and 3 also show the von Mises stress exhibited on stainless steel and titanium implant in various stages of bone healing.

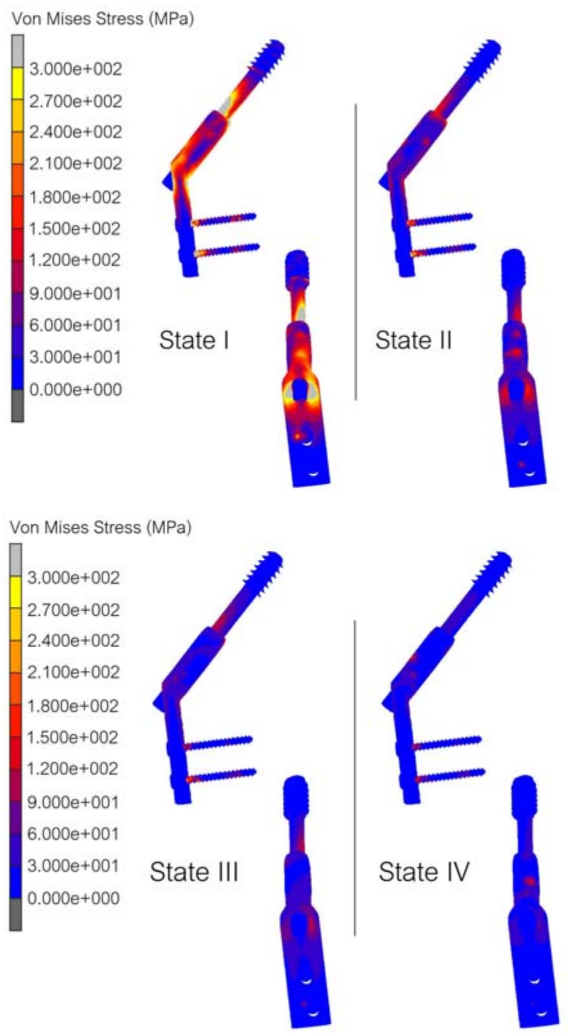

Fig. 2 The von Mises stresses on the stainless steel implant throughout healing process.

B. *Fracture site stability*

In order to evaluate the stability of the fracture site, it is necessary to monitor the elastic strain in the fracture site as it represents the deformation of material from their original shape under physiological loading. The lower elastic strain value in the fracture site presents the better primary stability of dynamic hip screw system. According to Table III and Table IV, it revealed that the stainless steel implant presented better stability than the titanium implant. Regardless of materials, at early stage of fracture healing, the stability of fracture sites was low, later stages, the stability of fracture sites increased throughout the healing process. In addition, after the implants were removed, the elastic strains were reduced to lower values.

TABLE III
MAXIMUM STRESS IN THE IMPLANTS AND ELASTIC STRAIN ON FRACTURE SITE

State	Stainless-DHS		Titanium-DHS	
	Max. Stress (MPa)	Fracture site Strain	Max. Stress (MPa)	Fracture site Strain
- *Stage I* (Early stage)	1,198.8	6.163e-1	1,022.5	7.958e-1
- *Stage II* (Healing)	539.7	1.654e-1	490.9	1.707e-1
- *Stage III* (Healing)	529.3	8.494e-2	325.9	8.770e-2
- *Stage IV* (Intact)	340.7	9.751e-3	247.2	9.286e-3
- *Implant Removal*	-	5.443e-3	-	5.443e-3

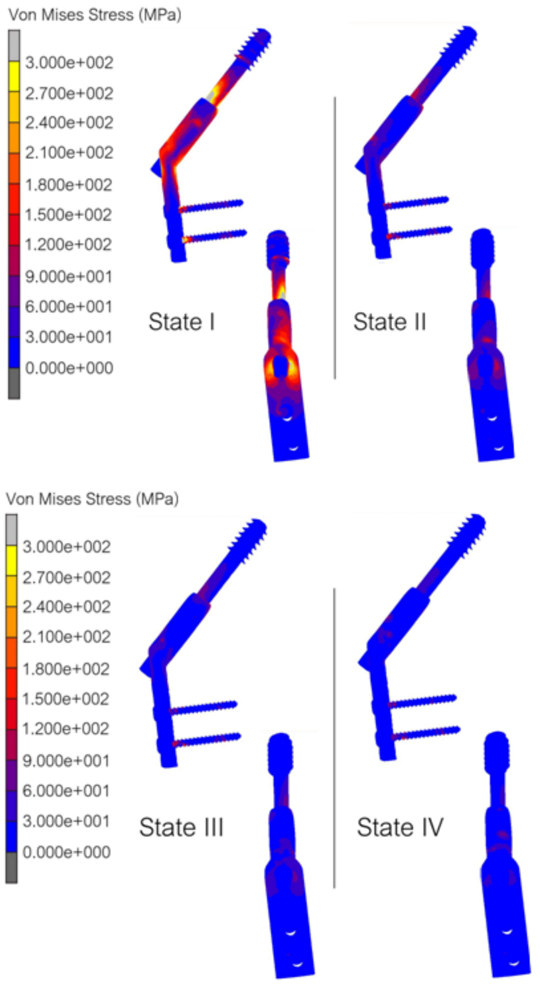

Fig. 3 The von Mises stresses on the titanium implant throughout healing process.

IV. DISCUSSION

Finite element analysis is an acceptable tool in investigation the mechanical performance of many orthopedic implants [13-16]. The boundary condition used in this Finite Element study was included muscle forces as well as joint reactions since previous studies have shown the importance [17]-[18]. One-legged stance condition was applied in this study have shown the critical assessment of dynamic hip screw mechanical performance.

In the early stage of bone healing, the high stress exhibited in the implant due to the elastic modulus of fracture site was low. Therefore, most of load transferred to stiffer material, in

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this case was implant. Therefore, it is not safe to walk with full-weight bearing as it increases the risk of implant failure. The recommendation is to avoid walking or walking with partial-weight bearing. Crutch and walker is helpful for patient at this stage.

One should also take into consideration is fracture stability at the fracture site. The lower elastic modulus presents the lower fracture stability (higher elastic strain). In the State I, full-weight bearing decreased the fracture stability. It is possible to be another cause of implant failure as well. Since partial weight bearing increases the stability of fracture site, it is important not to apply the full weight bearing at this stage.

Regardless of material property of implant, the magnitude of stress of implant turned to lower values throughout healing process as the elastic modulus of fracture size got higher. Some of weight bearing shifted from implant to bony structure. The titanium implant exhibited lower stress value in each stage throughout bone healing process than stainless steel implant. It seems to be safer to use the titanium dynamic hip screw, but the one aspect should be aware of is the elastic strain. The higher elastic strain during titanium implant stabilization could decrease the bone formation.

At the final stage of healing process, the magnitude of stress reduced to low value. However, it is important to consider the fatigue failure which generally occurs at a stress level below the yield stress of material. For stainless steel implant, the long-term retaining implant is not proper. Since the stress exhibited on stainless steel implant in the stage IV is not below the cyclic stress failure which the typical cyclic stress failure is 200-350 MPa. Therefore, removal of the stainless steel implant is needed. Moreover, the stainless steel implant removal increased the stability of fracture site. For titanium implant, the long-term retaining implant is possible as the stress in stage IV was below the cyclic stress failure of titanium which is around 550-700 MPa. Even, the fracture stability after titanium implant removal was slightly increased, but the difference was not significant.

V. CONCLUSION

In the initial stage of bone healing process, full weight-bearing should be avoided. Patient should walk carefully with aid of crutch or walker. The long term leave of stainless steel implant after bone formation should also be avoided as it could increase the risk of implant failure due to cyclic loading. In opposite way, using titanium implant for the long term leave is safe to do but, more attention must be paid about fracture stability.

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