Mechanical Performance Evaluation of Dynamic Hip Screw (DHS) for Trochanteric Fracture

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Abstract

This research presents evaluation of the mechanical performance of Dynamic Hip Screw in each stage of bone healing process as well as after the implant is removed. All analyses were performed based on the three-dimensional finite element model derived from computed tomography images. The assessment of the mechanical performance were used three parameters, Von Mises Stress to evaluate the strength of bone and implant, Elastic Strain to evaluate fracture stability and Strain Energy Density (SED) to evaluate the risk of secondary fracture. 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 as well as low fracture stability. In the late stage of bone healing, implant removal is strongly recommended in order to prevent the stress cyclic failure.

***Keywords**:* Trochanteric fracture, Dynamic Hip Screw (DHS), Finite element analysis

1. 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]. Aim of the trochanteric fracture surgery is to stabilize the fracture in reduced position and provide the early weight-bearing [1,5]. Beside trochanteric gamma nail (TGN), Dynamic hip screw (DHS) is also a widely accepted standard fracture fixation for treatment of 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 (recent after fracture) by means of mechanical testing [7,9]. During the healing process, the mechanical model for evaluation of the mechanical performance is difficult to set up. The observations of post-operative mechanical performances are usually accessed by radiographic image which allow the observation the possible implant failure or changing of bone at fracture site [10]. However, the access of mechanical performance evaluation from this method cannot be certain.

This study was aimed to evaluate mechanical performance of the 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 different healing stages were also accessed. By this way of study, stress distributions and fracture stability during early stage of healing process until late stage of healing process were able to investigate.

2. Methods 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.

2.1 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 (DHS) 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 femur model. The lag screw was aligned parallel to femoral neck axis. Later, the dynamic hip plate was also aligned parallel to femoral neck axis; 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.

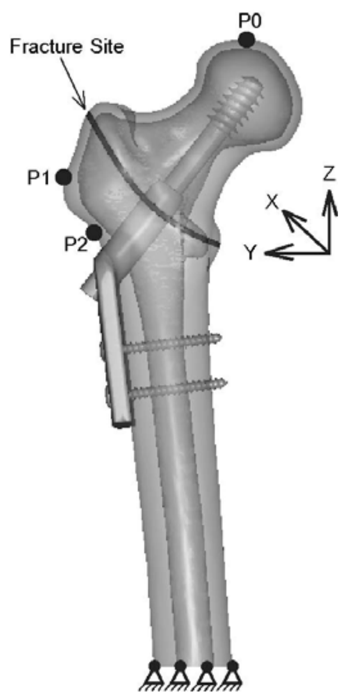

Fig. 1 Three-dimensional model of 2-hole dynamic hip screw stabilized the trochanteric fracture and the boundary conditions

Four-node tetrahedral elements based on Stereolithography (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.

2.2. 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 model of implant was assigned as a stainless steel. Corresponding elastic constants (Elastic Modulus and Poisson's ratio) used in this model were presented in Table 1.

2.3 Boundary Conditions

Table 2 and Fig. 1 present the loading conditions and boundary conditions described by Heller et al [14] 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.

Table. 1 Material properties applied for the finite element model. [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	

Table. 2 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

2.4 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.

3. Results

3.1 Stress Distribution

The evaluation the risk of the implant failure could be observed by maximum von Mises stress which exhibited on implant. The critical regions were considered to be at the lag screw and screw sets as the high von Mises stress were found. The von Mises stresses on the implant reduced to lower values throughout the healing process as illustrated in Fig. 2. Table 3 also showed the numeric values of the maximum von Mises stresses exhibited on implant in various stages of bone healing.

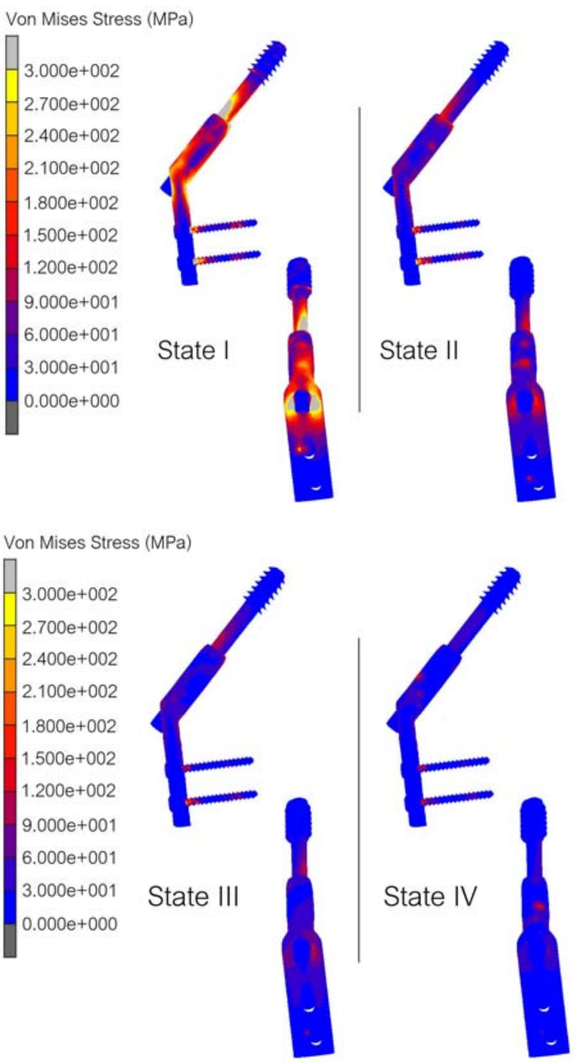

Fig. 2 The von Mises stresses on the implant throughout the healing process.

3.2 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. At early stage of fracture healing, the stability of fracture sites was low, later stages, the stability of fracture sites increased proportionally to the time of healing as shown in Table 3. After the implant was removed, the elastic strain was decreased from while it was retrained.

Table. 3 Stress in the implant (MPa) and Strain on Fracture Site (mm/mm).

Stage	Max. Von Mises Stress (Implant)	Max. Strain (Fracture Site)
Stage I (Early Stage of Fracture Healing)	1198.8	6.163E-1
Stage II (Healing)	539.7	1.654E-1
Stage III (Healing)	529.3	8.494E-2
Stage IV (Intact)	340.7	9.751E-3
Implant Removal	-	5.443E-3

3.3 Secondary Fracture

Secondary fracture is a common clinical complication after the bone formation process. The main causes of the complication may be from the bony structure subjects to large amount of loads after implant is removed [15]. Since this is a critical complication, it was necessary to observe Von Mises Stress and Strain Energy Density (SED) in the last stage of bone formation (Stage IV) and the stage of implant removal. Table 4 displays the parameters in each of bone components. Von Mises Stress and SED exhibited in all components decreased to lower magnitudes after the implant was removed, except for proximal cortex which was slightly increased.

Table. 4 Maximum Von Mises Stress and Strain Energy Density in various bone components during implant retained stage and implant removal stage.

Component	Stage IV (Intact)	Implant Removal
Max. Von Mises Stress (Proximal Cortex, MPa)	52.1	52.4
Max. Von Mises Stress (Proximal Cancellous, MPa)	9.1	5.6
Max. Von Mises Stress (Shaft Cortex, MPa)	140.7	67.7
Max. Von Mises Stress (Shaft Cancellous, MPa)	5.1	1.1
SED (Proximal Cortex, kPa)	95.53	97.22
SED (Proximal Cancellous, kPa)	71.54	21.62
SED (Shaft Cortex, kPa)	53.00	2.99
SED (Shaft Cancellous, kPa)	668.32	148.84

4. Discussion

Finite element analysis is an acceptable tool in investigation the mechanical performance of many orthopedic implants [15-18]. 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 [19,20]. 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 exhibits in the implant due to the elastic modulus of fracture site is low. Therefore, most of load transfer to stiffer material, in this case is 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. According to the study, approximately not over 60 per cent of full-weight bearing could be most appropriate.

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 decreases 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 should not be applied at this stage.

The magnitude of stress turns to lower values throughout healing process as the elastic modulus of fracture size is getting higher throughout healing process. Some of weight bearing shifts from implant to bony structure. At the final stage of healing process, the magnitude of stress reduces to low value. However, considering the fatigue failure which generally occurs at a stress level below the yield stress of material, the long-term retaining implant is not proper. Since the stress exhibits on implant in the stage IV is not below the cyclic stress failure which the typical cyclic stress failure is 200-350 MPa for stainless steel. Moreover, the removal of implant does not affect the stability of fracture site as the numeric value in stage of implant removal shows decreasing. In addition to stability aspect, the stresses and SED in most of bone components after the implant removal also turns to lower magnitudes. Even, both parameters in proximal cortex are slightly increased, but the value is not different to the stage IV too much. Therefore, the removal of implant is found to be safe and prevention the cyclic failure is achieved.

5. 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 implant after bone formation should be avoided as it could increase the risk of implant failure due to cyclic loading. Implant removal is necessary.

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7. References

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