Short Research Article

Contact Analysis for Coupling of Plates and Screws in Fracture Fixation of Cortical Bone

ABSTRACT

Internal fixation is a common treatment for bone fracture. Bone fracture occurs due to different reasons such as motor vehicle accidents, falling,…etc. The treatment is performed by fixing plate and screws to the fracture site. Lack of stability of the implants (plates and screws) may lead to delay in healing or failure of treatment. Micro-motion between the implant and the bone may cause formation of fibrous tissue around the screw which will lead to implant loosening. On the other hands, firm fixing of the conventional implants (Dynamic Compression Plates) may lead to delay resorption and delay in healing. Recently, Locked Compression Plates were introduced to get over the shortcomings of the existing Dynamic Plates. In Locked Plates the hole and screw head were threaded to provide more stability and reduce contact with the bone surface. In this communication we conducted computational analysis to compare the stability of both sets of implants. Results have revealed that Locked Plates provide more stable fixation and resistance to micro-motion. However, stress shielding might occur which will delay healing. Future designs of the Locked Plates can focus on improving stability and reducing damage to blood supply which will shorten the healing period. Computational analysis (finite element analysis) can be effectively used to guide these future designs.

Keywords: Internal fixation of bones, Locked plates in bones, Dynamic compression plate, 3-D FEA model for bone fracture

1. Introduction

Internal fixators is a common treatment for bone fracture [1 – 3]. Bone fracture, specially the femur fracture, is a serious health problem [3 – 4]. Long bone and humeral bone fracture may occur in falling, motor-vehicle accidents, sports related-incident and assault disrupts the stiffness of the bone and results in painful loss of limb function. Soft tissue complications such as reflex dystrophy which may disturb blood supply and cause pain due to immobilization [5]. Internal fixation (surgical stabilization using implants) restores continuous stiffness, abolishes pain and allows early mobilization. Mobilization of the articulations prevents soft tissue complications that were the rule after extensive external splinting of articulations by plaster cast. Still, internal fixation, especially when carried out without care, produces damage to the vascular support of bone and soft tissues.

Common method of internal bone fixation employs plates with simple holes for the screw and does not have any locking mechanism between the screw and the plate. While this method makes a firm initial contact between the bone and the plate it may become loose due to the movement of the screw and will not support the fracture site. As shown in Figure 1, the lateral relative motion may cause bone resorption [5].

On the other hand, locked plating, which through internal threads on the plate restrains the relative motion between the screw and the plate, can provide support for the fractured site while it is not firmly contacting the bone as shown in Figure 2. This feature is advantageous since it does not affect the blood circulation around the fracture site. Locked plating was first used in maxillofacial surgery and in spine surgery, and recently is used in orthopedic surgery. The use of locked plating has a particular advantage in patients with osteoporosis and in metaphyseal bone, i.e., the weaker bone that is close to the joints. In fact, the treatments of periarticular fractures, i.e., fractures that occur through the joint surfaces and extend below the joint surface, have been improved by the advent of locked plating. Some orthopedic plates have both locking and unlocking screw holes. However, the question of when and where to use Locked plates or Dynamic plates has received less attention in the literature.

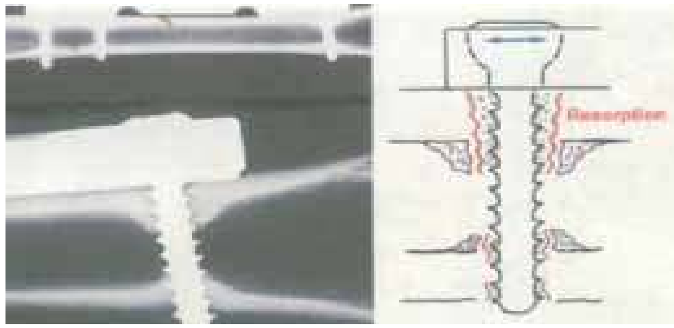

Figure (1): Loosening of the screw and plate construct in internal fixation. Resorption will occur in the contact area between the screw, the plate, and the bone. [5]

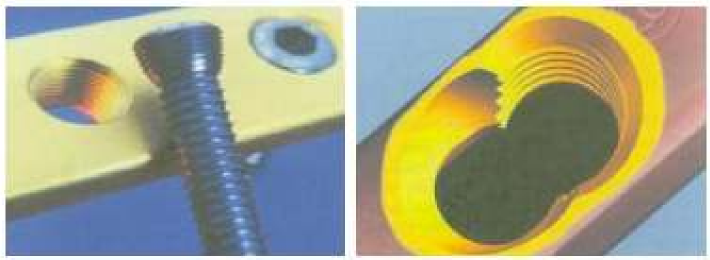

Figure 2: Locked plates and screws [5].

A number of models have been used to study the internal fixation of bones. Cordey and Perren introduced the composite beam theory approach with apparent limitation and deficiency to analyze the micro-motion between the plate and the bone [6]. Simon and Woo used very simplified 1D, 2D &3D models, concluding that these models needs improvement to quantify the stresses and strains in critical areas [7]. New designs suggested using stiffness graded plates to balance between required stiffness and biological priorities [8]. Many 2D FE models were introduced in many studies to analyze this problem, however the approximation of a complicated 3D FE model by simplified 2D model was the inherited error in all these studies.

The concept of biological internal fixation is still developing. The rigidity of the plates currently in use is a controversial subject. Bones re-fracture, screws failure and fatigue failures were observed. There is a need for research and development of structural analysis tools for the evaluation of current and future internal fixation plate designs in order to provide a plate that is strong enough to promote fracture healing yet not so stiff as to hinder bone remodeling.

2. Materials and Methods

The focus of the finite element analysis is on the two contact areas: first, between the screw and the plate and second, between the plate and the bone. The Discretized Geometrical Model (DGM) consists of 415 geometrical points and 180 volumes were created manually. The DGM volumes consist of hexahedron and prism volumes. The prism volumes were used to fit the conical shape of the screw head (6 mm diameter) as well as the whole screw shaft (4 mm diameter). The bone cross section is approximated to square cross section (20mm x 20 mm), length of the whole bone is 280 mm with a fracture gap of 10 mm. The plate rectangular cross section is 10mm x 4 mm. Two types of contacts between the screw and the plate are considered and modeled, rigid (representing locked) and sliding (representing dynamic contact). The Finite Element model of the bone and the plate were developed and shown in Figure 3 below using ADINA software (ADINA Inc., MA). For the locked surfaces of the plate and the screw a “Rigid Link” elements were used with the master and slave nodes. For the unlocked plate, the contacting surfaces were assigned. The assembly mesh has used 3D 8-noded Solid elements. The number of elements is 4608 elements for the bone and 6784 elements for the screws and the plate. The total number of nodes in the whole model is 13488 nodes. The advantage of this model is that it is very flexible and the geometry can be changed by moving points around to fit different designs of plates and screws. Details of creation the DGM and creating the mesh were detailed in previous work [9]. The model was subjected to bending (0.6 Nm), torsion (0.2 Nm), and shear (100 N) loads.

Plates and screws usually made of stainless steel or titanium. For this study the material is assumed to be stainless steel. Bone is assumed to be transverse-isotropic. The actual models in Figure 3 below were provided by the Orthopedics Department in State University of New York (SUNY) – Downstate Medical Center in Brooklyn.

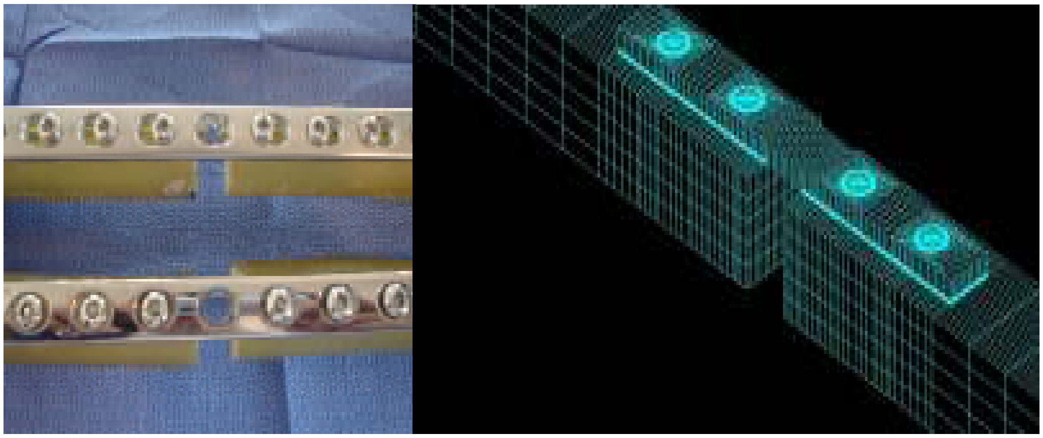

Figure 3: Experimental models (Dynamic and Locked plates) provided by Orthopedic Dept at SUNY-Downstate Medical Center (Left), Finite element model using four screws with high mesh density around the plate and bone construct to produce better results. Thick lines show the assignment of contact surface (Right). Details of the procedure used to build the DGM and creating the mesh is reported in our previous work [9].

3. Results

The analysis was run for ten time steps to observe the propagation of stresses in every step in both constructs. The maximum shear stress along the contact area between the bone and the plate is shown in Figure 4. The shear is observed to be higher near the screws especially the screw which is near the fracture site. In twisting, Von Mises stresses were plotted along the one side of the plate in the 5th time step as shown in Figure 5.

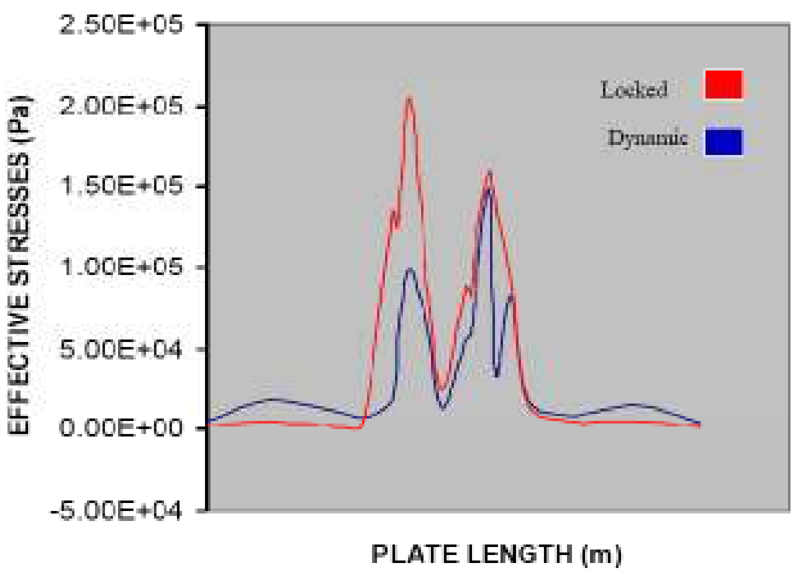

Figure 4: Comparison of developed shear stress on the bone contact surface in case of Locked and Dynamic plates over one screw (closer to fracture site)

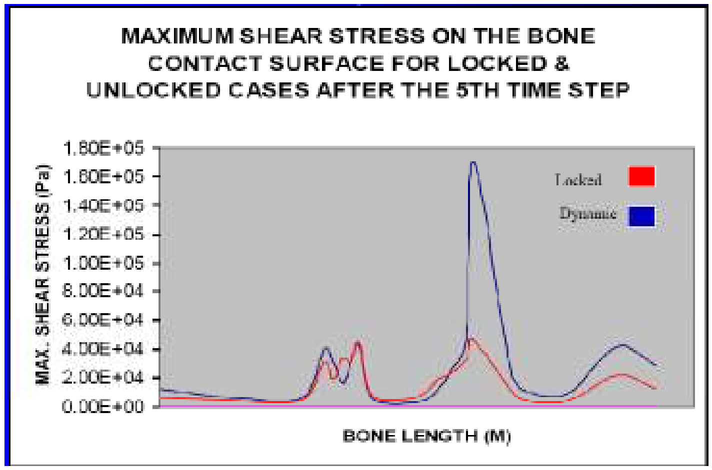

Figure 5: Effective stresses along one side of the plate near one screw for Dynamic and Locked plates. Stresses increase near the hole site closer to the loading location.

Stresses around the screw in torsion were analyzed also for different time steps in both plates subjected to the same loading as shown in Figure 6. The stresses observed to be higher for Locked plate till the 10^{th} time step while the Dynamic plate has failed to go beyond the 6^{th} time step, which is an indication of loosening and instability as shown in Table 1.

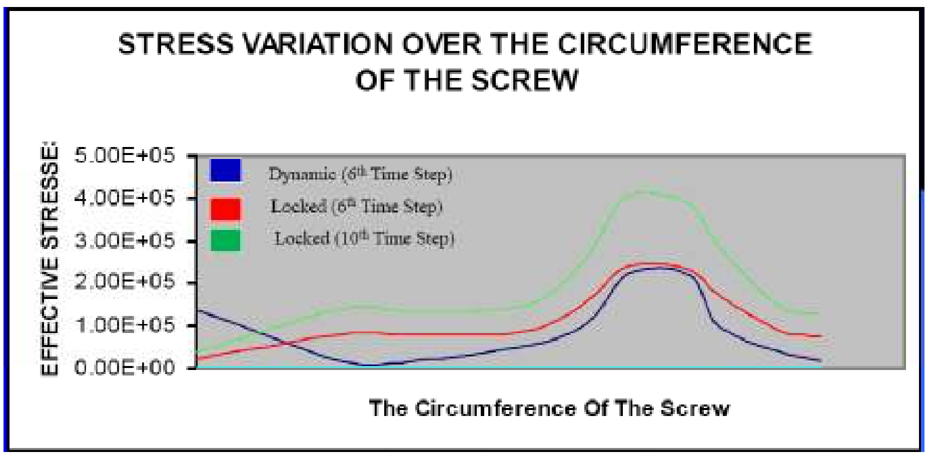

Figure 6: Stress variation (in Pascal) over the circumference of the screw at different time steps for Dynamic and Locked plates in torsion.

Table 1: Stresses induced in torsion (0.1 Nm) for Locked and Dynamic Plates in ten time steps

Plate Type	Maximum Stress	Stability after 10 Time Steps
Locked Plate	0.39 MPa	Stable
Dynamic Plate	0.26 MPa	Unstable after 5^{th} Time Step

4. Discussion

The main goals of fixation devices are to maintain anatomic alignment, stimulate healing process, and provide stability [10]. For locked plates the analysis shows development of high stresses around the screws as shown in Figures 5 and 6. This might be due to the resistance in the threads of the hole and the screw head. However, this accumulation of stresses lead to reduced stresses over the bone contact surface as observed in Figure 4 which will improve the healing time of the bone. Nevertheless, bone needs some stresses continue growing and healing but how much enough is enough will be the challenging question. On the other hand, two scenarios might be predicted. The first one is stress shielding where most of the stresses will be carried by the plate and screws which will cause weakness of the bone and longer recovery period. The second one is possibility of formation of plastic hinge due to increased stresses over the threads of the hole and the screw. This may lead to surface wear of the contact surfaces and release of tiny metallic particles that might be transported through the lymphatic system of the body to cause some implications. This might be avoided by improving the materials of the screws and the plates in that region to minimize the release of these particles. Pressure exerted by the plate on the bone surface may cause damage to blood supply and delay healing. To minimize vacscular damage less number of screws can be used [11]. The advantage of using Locking mechanism is that the plate may not need to get into contact with the bone. We will investigate this model in future communication.

To give a general view for the results based on Figures 4, 5, and Table 6 one should note that Locked plates carry more external loads with less deformation than Dynamic plates. Humeral Locking Plate will demonstrate improved rigidity and less hardware failure than standard Dynamic plates before & after cyclic bending and torsional loading in a humeral nonunion model [9, 12]. Dynamic plates might be useful for patients who have less active schedule such as senior citizens but may not be adequate for younger patients who have more active life style.

The maximum stress in the plate occurs at the fracture site where an unused screw hole, Figure 3, is generally located. It is recommended that the screw hole at the fracture site be eliminated. This reduces the stress concentration and increases the torsional and bending rigidity of the plate resulting a more stable implant. Future development of the construct may consider reducing the contact area between the plate and the bone as shown in Figure 7 but the effect of this decrease in stability should be investigated. The advantages of the FE model presented here is that it is flexible and the geometry can easily be changed by relocating specific geometric points to fit new plate construct without need for a long re-meshing process. The limitation of the model is in the number of screws used and approximating the bone geometry from semi-circular to rectangular.

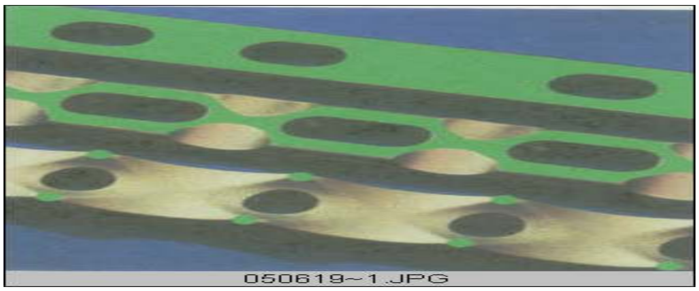

Figure 7: reducing the contact surface between the plate and the bone may improve healing, Perrin [1].

We have validated the FE model that is adopted in this study [9, 13]. Unlike previous studies of 3D finite element models in fracture fixation [14 – 16], this FE model is discretized in order to accommodate contact. Inherited in most of the previous 3D models used to analyze this problem, is the tendency to minimize the role of contact between components of the construct. Modeling 3D contact problems is one of tedious tasks in finite element analysis. The discretized model did not only address the contact issue, but presented a flexible geometry model that can be used by researchers to fit to different designs of implants that many include changing hole shape, Figure 2, plate and screw dimensions, and location of holes. The draw-back of the model is approximating the semi-cylindrical cross section of long bone by a square cross section. On the other hand, while most of the studies focused on compression loading scenario [14 – 15], the presented study addressed the scenario of torsion and bending. This communication will be extended in the near future to present a new study for compression forces to validate it against a recent study for experimental compression [15].

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Conflict of Interest

The authors declare that they have no conflict of interest

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