ORIGINAL ARTICLE

Stress Distribution and Stability Evaluation of Difference Number of Screws for Treating Tibia Transverse Fracture: Analysis on Patient-Specific Data

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ABSTRACT

Introduction: Screws placement may influence the stress distribution and stability of the plate and bone. Implant failures are normally happened in clinical practise when inappropriate number of screws is implemented. Therefore, intensive investigations are needed to provide additional quantitative data on the use of different number of screws. Therefore, this study was conducted to investigate the biomechanical performance of different number of screws configurations on Locking compression plate (LCP) assembly when treating transverse fractures of the tibia bone. **Methods:** Finite element method was used to simulate tibia bone fracture treated with LCP in standing phase simulation. To accomplish this, a three-dimensional tibia model was reconstructed using CT dataset images. 11 holes of LCP and 36mm of locking screws were developed using SolidWorks software. From this study, there are three models in total have been developed with different number of screws and screw placements. A diaphysis transverse tibia fracture of 4 mm was constructed. **Results:** In terms of stress distribution, all configurations provide sufficient stress and do not exceeding the yield strength of that material. **Conclusion:** In conclusion, eight numbers of screws were the optimum configurations in order to provide ideal stability to the bone with displacement of 0.37 mm and 0.91 mm at plate and bone, respectively.

Keywords: Number of screws, Tibia plate, Finite element, Biomechanics, Transverse fracture

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INTRODUCTION

According to the National Trauma Database (NTDB), the highest occurrence of bone fractures is the tibia bone with 33.9% from all the recorded injuries (1). This is because tibia bones have a vast range of motion and is exposed to incidents and trauma such as occupational hazards, vehicle accidents, high energy falls, sports injuries, and osteoporosis. One of the common ways in modern medicine is by introducing the plate and screws systems that binds the bone together to reach anatomical reduction for adequate healing.

Open reduction and internal fixation (ORIF) have become the standard treatment to treat long bone fractures. It is proven in clinical studies that Locking Compression plates are very effective in treating simple and complex fractures ranging from simple transverse to comminuted fractures (2). Nevertheless, locked plating failures still occurs due to flawed device configuration for the fracture pattern. According to MacLeod et al. [7], the complications of using compression plates onto the bones were found to be 15% among patients follow by 12.7% rate of re-operation. These conditions can occur due to lack of or over excessive of compression at the fracture site. Therefore, preoperative strategy and implementation of plate and screws configurations are important factors for bone healing process.

Interfragmentary motion (IFM) are pivotal in bone healing. IFM range has direct correlation with rigidity of the bone implant, where the plate that contains the screws that distribute the stress of the bone into the plate and give its stability (3). Another previous study suggested that IFM motions at the fracture site are most optimum from 0.1 mm to 0.4 mm that promotes bone healing and stability of the system for ambulation (4–6). Thus, compression plate configurations in number of screws must be achieved at optimum IFM range.

Many studies have indicated that failures of implants such as locking plate breakage, screw loosening and pre-prosthetic re-fracture have significant correlations with screws positioning variables such as the spacing of the screws and the numbers of screws (1, 3, 7). Such occurrence of excessive of screws stiffness and the lack of it, can hinder and restrict healing. Therefore, meticulous preoperative planning is important to prevent such implant failures. Hence, this study was conducted to investigate how different numbers of screws will affect the bone-implant system (7–9). There are three clinical aspects and consequently biomechanical demands in treating fractured bones which are: (i) the implant must support fracture healing, (ii) not deteriorate during healing period and (iii) should not loosen or caused patient discomfort (7,10).

MATERIALS AND METHODS

Three-Dimensional Bone Model

In this study, a three-dimensional (3D) dataset of tibia bone were obtained, modified and preprocessed before went through multiple stage of simulations. The model was acquired and sampled from a 22 years old male, that weights for 80 kg, possess a healthy overall condition and average Body Mass Index (BMI), verified from Hospital Tunku Ampuan Afzan, Kuantan Pahang, Malaysia. The 3D model was reconstructed from Computed Tomography (CT) data with the courtesy of the Hospital's imaging department. The use of the CT dataset has been approved by the ethical committees from the hospital. The model then was rebuild using a modelling software (Mimics Medical 21.0, Materialise, Belgium) for further inspections and tests to make sure its quality and validity. Next, to obtain an excellent analysis result, our model must be free from data noise, which have been done by implementing segmentation and masking process of the 3D tibia bone. Furthermore, the 3D model went through a few adaptations and corrections to make sure the size and dimensions of the bone are aligned with the real geometrical conditions that resembles a tibia bone. A transversal fracture with 4 mm width was constructed using Mimics Software accordance to a standard study done by Fagelberg et al. [11]. Then, the 3D model was reticulated with 3 mm triangular and adapted in Stereolithographic (STL) format for the next procedure. The use of triangular or tetrahedral mesh element for bone finite element modeling is acceptable as demonstrated by many scholars in their previous published papers (5, 8, 14, 16, 20), even though the hexahedral elements are providing more accuracy on the results. By validating the FE model via experimental works demonstrated that the tetrahedral element is enough and optimum to be used in the FE model for further analysis (5).

Locking Compression Plate Design

The Locking Compression Dynamic Compression (LC-DC) plate were constructed and built by a computer aided design (CAD) software, SolidWorks (Dassault Systemes, USA). The designed constructions have two components which are the uniplanar plates, and the locking compression screws which dimensions are specify on the standard measurement product of Synthese where the width of the screws are 4.5 mm and the length of 36 mm [12]. The length of the plate with 11 holes are set at 185 mm [13]. Figure 1 shows the overall geometry shape of the implant. Once the designed are completed, both the LC-DC plate and screws were arranged in a standard surgical positions and construct as a singular unit in the same software. The complete plate fixators and screws design was reticulated with triangle mesh elements of 1.5 mm in size. The last step for this stage, similar with the 3D model of tibia bone, it was adapted in Stereolithographic (STL) format to be exported into the next medical CAD software. These processes are repeated with LC-DC plates with 4 screws, 6 screws and 8 screws.

Simulated Virtual Surgery

A virtual surgery for the insertion of implant in bone was done in the Mimics software. The allocations of the plate-to-bone are place at the lateral surface of the tibia, upon standard surgical procedure (11). In this study, there were 3 configurations of LCP with 8, 6 and 4 screws. Next, to fixate the compression plate with screws onto the bones, the 3D implants were placed into the tibia bone model using a tool in the Mimics software of type create manifold assembly. This process required modifications to alter the non-uniform triangle mesh element into uniform size of element at the screws-bone intersection. These processes were simulated using the 3-Matic software. All the completed models were saved in STL files and ready to be exported into the analysis software. Figure 1 shows the assembly part of the locking compression plate with the screws.

Biomechanical Structural Analysis

Finite element analysis (FEA) was carried out using Marc Mentat software (MSC.Software, Canada). To further investigates, the file models were transformed into linear prime order tetrahedral structure (12). The properties of the LC-DC plates with screws were allocated to stainless steel with 200,000 MPa and Poisson's ratio of 0.3 (6). Meanwhile, for the tibia bone the material properties are set to 16,200 MPa and the Poisson Ratio of 0.3 (6). In the Marc Mentat software, all the components were designated with isotropic and homogeneous material properties. The mesh dimensions for the compression implant were set to 1.5 mm while the mesh dimensions for tibia bone are determined to be 3 mm. These configurations were obtained from a convergence analysis that were using multiple iterations process call refinement method (15). It was further proven by a previous literature from Ramlee et al. (15)

on finite element model. On top of that, the model has been validated through an experimental work from our previous study (5). From the validation work, a synthetic bone was used to measure strain at four different locations when 100N load was applied on the proximal region. The same boundary condition was applied to the FEA model, and the same location of strain were measured. From the findings, it shows that the FEA results agree with the experimental measurements. Therefore, the model was validated to be used for further analysis. Figure 1 shows the configuration of LCP with a) 8 number of screws, b) 6 number of screws and c) 4 number of screws.

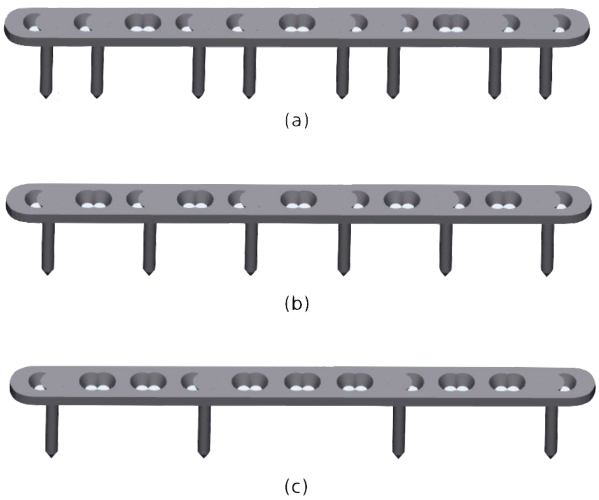

Figure 1: Configurations of Locking Compression Plate (LCP) with difference number of screws; a) 8 screws b) 6 screws c) 4 screws.

The final stage of this study was to conduct a simulation of a simple stand condition onto the bone and implant system. It is a standard procedure to investigate the implant performance in a stance phase conditions to measures its stability and stiffness. A study done by Oken et al. stated that 50% of the body weight was applied to one leg of a human body (18). Therefore, a total of 400 N load was set to the proximal tibia bone due to the sample subjects were weights at 80kg. The division of the load were applied onto the surface of medial curvature of the proximal tibia bone with 60% (240 N) and the surface of lateral curvature with 40% of the total loads (160 N) as shown in Figure 2 (16). In many previous studies, the vertical compression force was applied to emulate the weight bearing condition. In this study, the results in terms of von Mises stress and displacement were recorded from the simulation.

RESULTS

Von Mises Stress Distribution

The maximum magnitude of von Mises stress (VMS) of screws are concentrated at the edge of the screw and

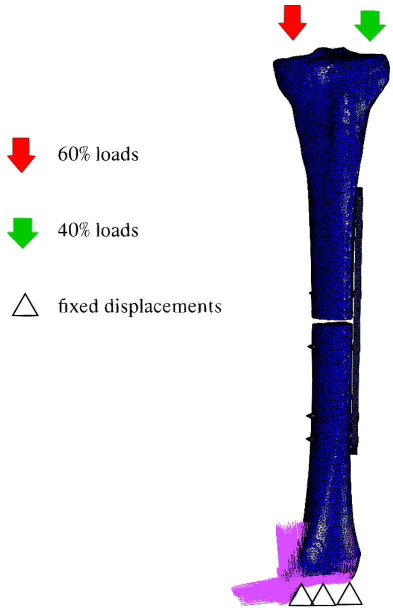

Figure 2: Boundary conditions of the finite element analysis

bone assemblage and at the tibia bones plate. The contour plot of VMS is illustrated in figure 3. Generally, the LC-plate have higher stress distribution compared to the bone and the system with tibia bone and 4 screws LC-plate has the highest VMS magnitude on both plate and bone. The measurement of magnitude during standing simulations at LC–plate with 8 screws are higher (36 MPa) than with 6 screws (30 MPa). While for LC-plate with 4 screws, has a high magnitude (69 MPa) which is two times larger compared to LC-plate with 8 screws and 6 screws.

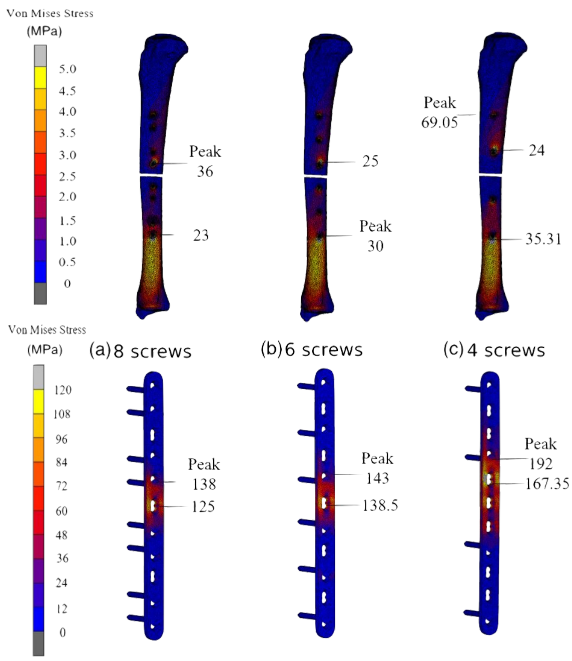

Figure 3: Von Mises stress contour plot of tibia bone and plate, with difference number of screws; a) 8 screws b) 6 screws c) 4 screws.

Relatively, it is different for stress concentration at the bone plate. Overall, the magnitude of stress at the LC-plate are not much different, but there is clear distinction of magnitude level. For LC-plate with 8 screws, the maximum VMS is 138 MPa, for LC-plate with 6 screws the peak VMS is 143 MPa which are not high in increment but LC-Plate with 4 number of screws does have higher maximum of VMS which is at 192 MPa. The trends of decreasing number of screws in LC-plating show increasing stress concentration at both tibia bone and LC-plate. Figure 4 is illustrating a histogram of maximum VMS for all models to show the increasing trend.

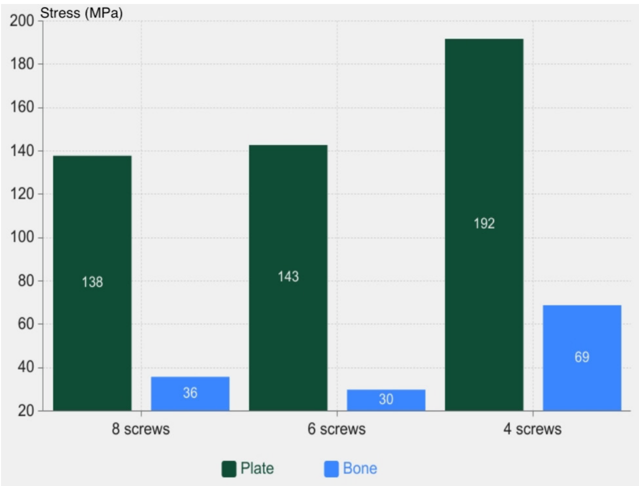

Figure 4: Comparison of maximum von Mises stress at the plate and bone models

Displacement

Figure 5 shows the contour plots of displacements of full construct for all three models. From the results, in general, it could see that LC-plate with 8 and 6 screws relatively have the same magnitude at its peak displacement, which is 0.91 mm and 1.01 mm, respectively. Both models also have the same value of displacement at the fracture site which is 0.25 mm. On the other hand, contour plots displacement of 4 screws model has a higher magnitude compared to the 8 and 6 screws models (2.22 mm). To be noted, the value of displacement at the 4 screws model are twice higher than the other models.

The trend of displacement at the LC-plate is another interesting finding. As number of screws decreases the displacement of the plate increases. These can be seen at LC-plate with 8 screws that demonstrated the value at 0.37 mm and 6 screws with 0.43 mm. LC-plate with 4 screws shows the highest displacement of 0.96 mm as it is twice the magnitude of the other models. Figure 6 shows the histogram of the displacement for LC-plate with different screw numbers.

DISCUSSION

Bone-implant models with 4 screws shows the highest magnitude of VMS located at the bone (69.05 MPa)

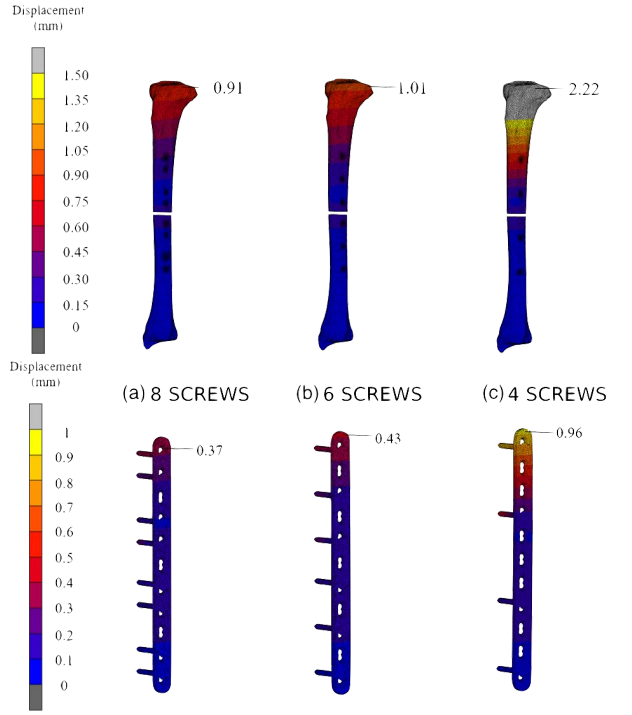

Figure 5: Displacement contour plot of tibia bone and plate, with difference number of screws; a) 8 screws b) 6 screws c) 4 screws.

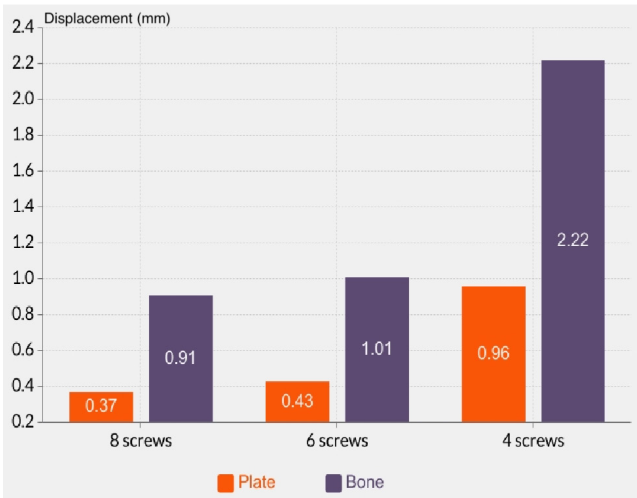

Figure 6: Comparison of displacement at the plate and bone

which are twice the magnitude of LC-plating with 8 and 6 screws which are at 36 MPa and 31.25 MPa, respectively. The maximum VMS on the bone for 4 screws LCP construct was appeared at the posterior hole of the most proximal from the fracture site, the hole of the first screws at the tip of the plate. This is due to the reduction number of screws that theoretically could reducing stress distributions taken to the plate from the bone, which cause bone to bear more loads. These gradually caused high deformations to the bone and loosen its stability. The bone with 4 screws has the highest peak displacement of 2.22 mm which can lead to delay healing to the bone as well as displacement at the fracture site of 0.48 mm that exceeds the optimum range of IFM (4). As compared with LCP construct with

8 and 6 screws, the displacement value was only 0.91 mm and 1.01 mm, respectively, where this shows at least 145% difference. In overall, LC-plating with only 4 screws are not sufficient enough for fixation stability and stiffness for the fractured bone, and this is in agreement with a previous study (19). Relatively, a study done by Lee at al. that were using femur bone also obtained quite similar pattern of results for LCP with 4 screws that generated displacement value at 7 mm while 6 screws was only 5.63 mm and for 8 screws was at 5.47 mm. The findings also concluded that LCP with 4 screws is not sufficient for the bone stability in axial compression loading. On the other hand, LCP with 6 screws shows no much difference with 8 screws (19). Additionally, another study by Stoffel et al. where they conducted about the numbers of screws affecting LCP mechanical performance concluded that 3 number of screws per bone fragment is not contributed to increase its axial stiffness. This study also proved that every addition of screws may only increase in 8% in axial stiffness.

From the results, the LCP with 4 screws showed high displacement of the bone is not only delaying healing process but risk to the plate as well as which can cause it to be loosen over time. The stress at the plate is 192 MPa which are nearly to its yield strength of 215 MPa. Overtime, the plate can experience breakage, screws loosening and bone re-fracture (7,11,20). Furthermore, the LC-plating with 8 number of screws and 6 number of screws relatively have quite similar magnitude in both stress distribution (138 MPa) and (143 MPa) respectively. As well as the deformation of the plates are also not much difference where 8 screws plate have displacement of 0.37 mm while 6 screws demonstrating displacement at 0.43 mm. In general, both plating configurations indicate that the plates are optimum to give stability and axial stiffness to the bones and provided ideal IFM motions at the fracture site to promote bone healing and unions. In comparisons, LC-plating with 6 screws could provide sufficient biomechanical stability to treat tibia bone fractures as good as LC-plating with 8 screws. These reductions are acceptable t as the screws are positioned fairly to both further and nearer to the fracture site (21,22). Therefore, it is more ideal to have lower number of screws as it is affective enough to promote healing (23). Worth to know that, this is more feasible options as it would reduce the damage to the tibia bone and soft tissues, operation costs, lowering surgery time, preventing from further complications for the patients to bear (24,25). (24)(25).

Some simplifications have been made in the finite element analysis. First of all, the use of isotropic, linear and homogeneous properties for the bone model. To be noted, the bone is not behaved in isotropic and homogeneous properties, but rather in anisotropic and inhomogeneous properties. However, due to the limited computer resources to simulate complex properties, therefore, this could not be avoided. Nevertheless, the same method of using isotropic, linear and homogeneous properties have been used by many other scholars with acceptable results, and the FE model was validated via the experimental works (12, 16, 17, 26, 27). The other simplification was regarding the use of single data and property of bone in the simulation. It is suggested that further studies can be conducted to evaluate different boundary conditions and material properties, so that it can give a newer insight to the researchers to conduct future studies (28).

CONCLUSION

The present study analysed the von Misses stress and displacement of transverse fracture for tibia bone under different number of screws for LCP (8 screws, 6 screws and 4 screws). It is proved that LCP with 8 and 6 screws configurations proved to be optimum condition for providing enough stability in treating the fracture. LCP with 4 screws construct demonstrated the lowest stability performance and reach maximum stiffness that will cause breakage in the long run. Lastly, LCP with 8 screws gives off the same performance with 6 screws but it is redeeming undesirable as it is excessive and costly. Further validation of this outcome is required in the future in terms of experimental works in laboratory.

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