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BIOMECHANICAL EVALUATION OF LOCKING COMPRESSION PLATE (LCP) VERSUS DYNAMIC COMPRESSION PLATE (DCP): A FINITE ELEMENT ANALYSIS

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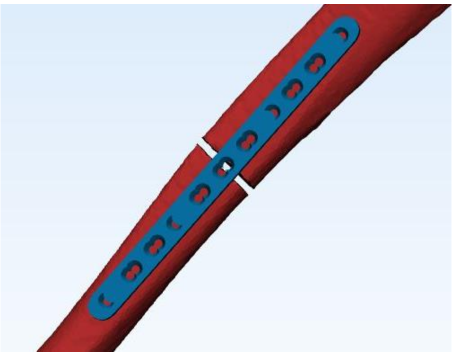
Graphical abstract



Abstract

Internal fixators are commonly used to treat long bone fractures, its aim is to provide interfragmentary compression, allow limited micromotion and provide stability to the bone for ambulation. However, complications such as non-unions, malunions and broken implant, can occur due to the complexity of mechanical force acting on the bone-plate models. Therefore, this study is proposed to investigate the biomechanical characterization of plate design on a tibia bone using finite element method. Two different designs; 1) locking compression plate (LCP) and dynamic compression plate (DCP) were simulated by using Marc.Mentat software. From the findings, the LCP have lower peak von Mises stress (VMS) distribution of 160 MPa compared to DCP with VMS value of 232 MPa. Surprisingly, the VMS of DCP plate system have exceed the yield strength of stainless steel (215 MPa) which translate to higher risk of failures. Moreover, the DCP plate system shows 50% lower stability compared to the LCP plate system, which has the peak displacement at 0.98 mm compared to the DCP bone at 1.53 mm. In conclusion, the LCP provides better stability and stress distribution up to 45% differences as compared to the DCP.

Keywords: Locking Compression Plate, Dynamic Compression Plate, Von Mises Stress, Displacement, tibia

Abstrak

Penetap dalaman sentiasa digunakan untuk merawat tulang panjang yang patah, dengan tujuan untuk menwujudkan tekanan *interfragmentary*, membenarkan pergerakan mikro, dan menyediakan kestabilan kepada tulang untuk sembuh. Walaubagaimanapun, komplikasi seperti tiada kesembuhan, kesembuhan yang cacat, dan implan patah, boleh berlaku disebabkan daya mekanikal yang bertindak kepada tulang-implan. Justeru itu, kajian ini telah dijalankan untuk mengkaji sifat biomekanikal rekaan implan tulang tibia menggunakan kaedah *finite element*. Dua rekaan; 1) *locking compression plate* (LCP) dan *dynamic compression plate* (DCP) telah disimulasikan menggunakan perisian Marc.Mentat. Hasil kajian menunjukkan LCP memberikan tekanan *von Mises* yang rendah iaitu 160 MPa berbanding DCP iaitu 232 MPa. Hasil ini menunjukkan bahawa tekanan pada DCP telah melebihi kekuatan *yield* bahan keluli tahan karat (215 MPa) dan menunjukkan risiko tinggi untuk patah. Tambahan itu, rekaan DCP menunjukkan 50% kurang stabil berbanding rekaan LCP, dimana anjakan DCP adalah 1.53 mm berbanding 0.93 mm untuk LCP. Kesimpulannya, rekaan LCP memberikan kestabilan dan peredaran tekanan sehingga 45% beza berbanding rekaan DCP.

Kata kunci: *Locking compression plate, dynamic compression plate*, tekanan *von Mises*, anjakan, tibia

1.0 INTRODUCTION

Regardless of the robust properties of bone, it is very common for people to experience fractures in their lifetime. To date, one of the most common fractures in human lower limb is tibia fracture. This common fracture is normally happened due to the fact that the mechanism of injury (MOI) is vast such as high energy falls, sports injury, vehicle accidents, occupational hazard and in some cases of osteoporosis [1]. According to the National Trauma Database (NTDB), tibia and fibula fractures are found to be the most common fractures and has the highest percentage of 33.9% as compared to other injuries [2]. These data is strengthen with the findings in Journal of Children's Orthopedic that tibia fractures is one of the most common injuries that children experienced and is associated with high cost of treatment[3]. Depends on the severity scale of injury, tibia fractures can fall into severe and complex categories of fractures that require direct healing due to disfiguration of bone structures and build up pressures that prevent bone to heal normally. Therefore, the usage of plate screw construct enables reconstruction of anatomy, bony alignment and at the same time provide compression needed for bone healing.

Fractures cause discomfort and pain to patients. At the same time bone alignment can be very tricky to be corrected and achieved with the original anatomical structure [4]. From many surgeons, the technique of open reduction internal fixator (ORIF) is one of the most effective method in promoting bone healing through interfragmentary compression and provide an anatomical frame for the bone to grow [5]. This technique uses an internal compression plate which is screwed into the bone to provide stability. The plates come in two classes which are dynamic compression plate (DCP) and locking compression plate (LCP) where both uses compression screws that tighten the plate to the bone and locking screws that have threads on its head to fasten on to the plate and the bone, respectively. However these methods shows a lot of regressions as the configurations between the plates can cause disturbance to the healing soft tissue of the surrounding, hinder callus formations and ineffective placements of screw that does not build up enough compressions for the bone to heal [6] .

Complication rate are found to be 15% among patients and follow by 12.7% rate of re-operations. These cases were reported due to malunion, screw cut-out and avascular necrosis (AVN), where this is a symptom of death bone condition in which bone do not obtain blood supply, consistent pain and impairment. These conditions can be happened due to lacking of or over excessive of compression of the fracture site [7]. Several plating techniques were introduced by the medical practitioners such as Locking Compression Plate (LCP) and Dynamic Compression Plate (DCP). However, there is no specific study on the differences between those two different techniques from the literature that focusing on the stance phase condition (50% load from body weight) of a gait cycle, especially in terms of biomechanical perspective. As far as authors aware, no other studies were found from previous literature that demonstrated results of finite element analysis between LCP and DCP plates. Therefore, the aim of this study is to investigate the biomechanics effects of the different plate design; 1) LCP and 2) DCP when treating transverse tibia fracture via finite element analysis. The stability of aforementioned plates was investigated where stress and displacement were predicted in both fixators and bone. From this study, it is expected that the results could be used by medical surgeons not only to justify their choices of plates usage but could be also a potential further analysis in the future clinical studies.

2.0 METHODOLOGY

Figure 1 shows the flow of work in this study. It starts with the three-dimensional (3D) modelling of bone, followed by 3D designing of plate, virtual surgery, and finite element analysis.

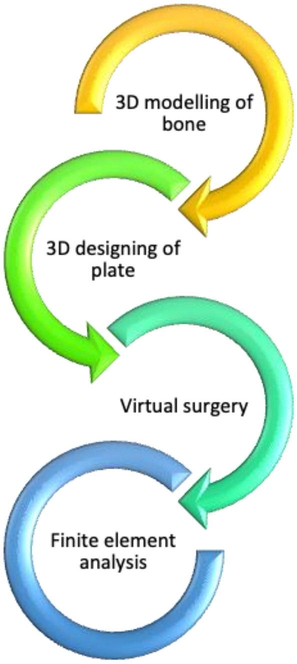


Figure 1 Workflow of the methodology

2.1 Three-dimensional Modelling

A dataset from Computed Tomography (CT) images of healthy subject was used to reconstruct a three-dimensional (3D) model of tibia bone. The weight and age of subject was 80kg and 22 years old, respectively. All procedures of data acquisition were done in Hospital Tunku Ampuan Afzan, Kuantan, Pahang, Malaysia. To reconstruct the 3D model, segmentation process was done via a modelling software, Mimics (Materialise, Belgium) [8], [9]. In order to remove data noise, a repetitive masking process using tools of 'draw' and 'delete' was done. To make sure the geometry of bone could mimic original shape, a repetitive modification including segmentation and masking process were made, then comparing with shape according to an anatomy book. Finally, the geometrical shape was confirmed by an orthopaedics surgeon from University Malaya Medical Centre (UMMC), Kuala Lumpur, Malaysia [10]. Once the intact bone of tibia was reconstructed, further step was taken where to create a transverse fracture. Cutting tools was utilized to conduct such step where the 3D model of tibia bone mimics 4 mm gap fracture as suggested by Fagelberg *et al*. [11]. Finally, the 3D model was saved in stereolithography (STL) format that can be used for later methods [10].

A computer-aided design (CAD) software, Solidworks (Dassault Systemes, USA) was used to design a uniplanar-unilateral of Locking Compression-Dynamic Compression plate (LC-DC Plate). As for the dimensions, it was referred to the commercial product of Synthes in which the screw diameter and length is 4.5 mm and 36 mm, respectively [12]. Meanwhile, the length of the plate with 11 holes were set at 185mm each as suggested by previous study [13]. Each of the solid bodies were then assembled into one single rigid body using Solidworks software. The 3D model of LC-DC plate is illustrated in Figure 2. Both plates were then saved in STL file for next pre-analysis steps.

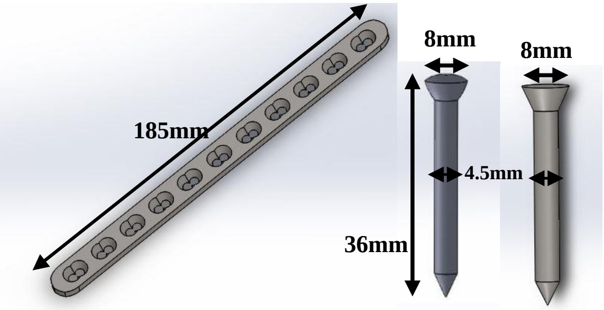


Figure 2 Locking Compression – Dynamic Compression Plate with conventional screws and locking screws

2.2 Simulated Implant Placement

Virtual surgery was done to place the plates onto the bone. This procedure was conducted in another CAD software, 3-matic (Materialise, Belgium) where the position of bone-to-plate was fixed at the lateral surface of the tibia bone [14]. Both LCP and DCP consisted of 6 different screws that were placed on the hole of plate. For the next step, a tool called 'create manifold assembly' was used to assembly both bone and plates together. Figure 3 is showing the fixation techniques for a) Plating1 of LCP b) Plating 2 of DCP.

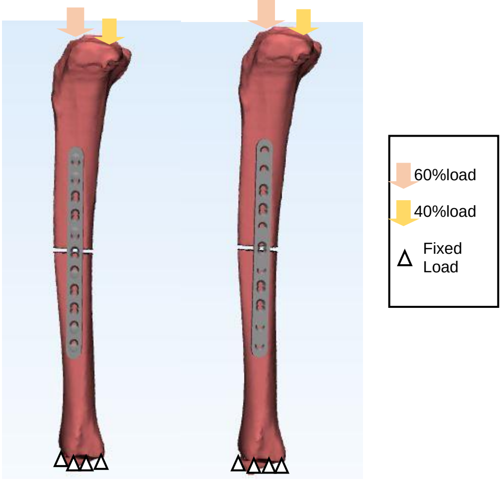


Figure 3 Techniques of fixation for a) LCP and b) DCP

2.3 Finite Element Analysis

Prior to finite element analysis, pre-processing must be done where all STL files were imported into a software, Marc.Mentat (MSC.Software, Canada). By using Marc.Mentat software, the STL files were then segmented into first linear order tetrahedral elements. It is known that the tetrahedral elements was normally used by many other studies in the literature to simulate human bone and implants for finite element analysis [15]. In terms of material properties of tibia bone, the Young's modulus and Poisson's ratio was set at 16,200 MPa [16] and 0.3 [17], respectively. For the LCP and DCP, the Young's modulus and Poisson's ratio was set at 200,000 MPa and 0.3, respectively [18, 19]. The chosen of the materials were based on the previous literature that demonstrated the properties are similar with real condition of bone and plate [16, 17].

To make sure the model is reproducible, a convergence analysis was performed prior to this study. H-refinement method was used to simulate 5 different bones with different mesh sizes and it was found that the model of bone and fixator was converged at 3mm and 1.5 mm, respectively [10]. Apart from that, a validation study was also conducted where the 3D model was found validated in terms of strain values [18].

In order to differentiate the contact condition between LCP and DCP fixation on the tibia, the friction coefficient of the system was determined, where LC-plate are 36% higher than DC-plate which is 0.4 and 0.26 respectively [14], [19], [20], [21], [14], [22].

For a boundary condition, one cycle from gait was chosen in which stance phase. This condition was used to indicate the first trial and moment of patients when start to walk. A total of 50% of the body weight (BW) in which 400N was axially applied to the proximal of tibia bone [8]. From there, 60% was axially applied to the medical curvature and another 40% was axially applied to the lateral curvature of tibia bone [21]. Meanwhile, the distal part of tibia bone was fixed in all directions to prevent any movement during the simulation. An illustration of the boundary conditions is shown in Figure 3. From the finite element analysis, von Mises stress and displacement were measured and compared.

2.4 Model Validation

From our previous study [10, 18], the tibia bone model has been undergone convergence analysis and validation works. Convergence analysis showed that the model has been converged at mesh size of 5 mm and 1.5 mm for tibia and external fixator, respectively. For the validation work, a one-to-one comparison has been done between FE model and experimental work. A synthetic bone has been used in this comparison where compression load has been applied onto the tibia. From the results, it showed that the FE model and experimental work were in the similar pattern of vertical strain when the bone was compressed with a load until 100 N.

3.0 RESULTS AND DISCUSSION

3.1 Von Mises Stress

Contour plots of the Von Mises Stress (VMS) for tibia bone for both DCP and LCP is illustrated in Figure 4. In general, the contour plots of all the configurations showed stress at the plates are higher than the bones. For the axial load compression test, the maximum von Mises stress value observed at the tibia bone with LCP is 31.25Mpa. While the tibia bone with DCP is 33.2 MPa, which shows no significant difference, with only 6% percentage different.

Other than that, stress concentrated at the screw plate system for both Locking Compression Plate and Dynamic Compression Plate is comparatively have higher magnitude of stresses than the bone during stance phase. For the Locking Compression Plate, the maximum VMS is 160 Mpa while Dynamic Compression Plate have 232 Mpa which is 48% higher compare to LCP. From the contour plot, it can be seen that the distribution of stresses have accumulated at the screw–plate interfaces, rather than other regions.

To be noted, our results demonstrated low stresses (160 MPa and 232 MPa for LCP and DCP, respectively) since the load conditions applied in this recent study were in stance phase, in which 50% of body weight. As compared with the previous literature, results from a study by Zhou *et al.* [19] shows high stresses (856.1 MPa) since the boundary condition of their study simulate 238% of body weight. This situation of different stress value is predictable and acceptable due to the fact that the boundary conditions for both studies were not in the same, thus a one-to-one comparison could not be analysed. Apart from that, it was found that the same location of high stress occurred at the centre of plate as demonstrated by Gailani *et al.* [22] and Izaham [12]. Our studies are also showing the same trend where high stress occurred at the middle part of implant (Figure 4).

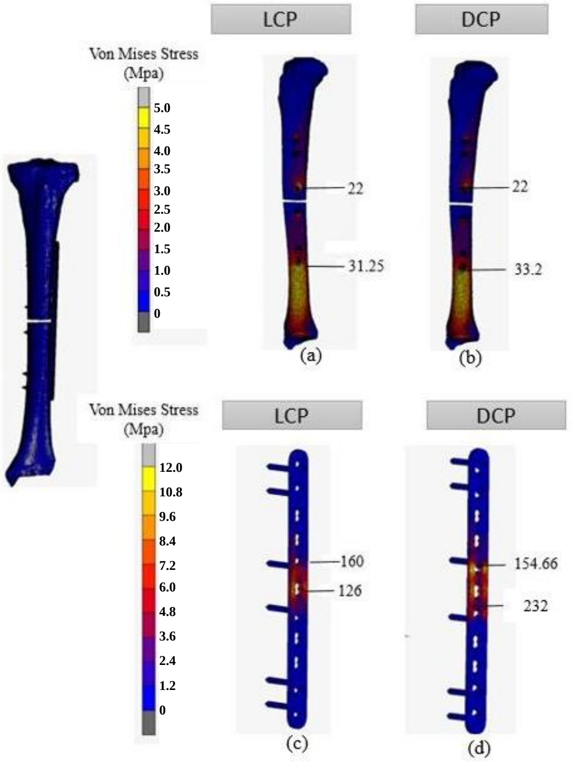


Figure 4 Contour plot of VMS distribution: a) Tibia bone with LCP plate, b) Tibia bone with DCP plate, c) LCP plate and d) DCP plate

3.2 Displacement

Many researchers have used displacement to show the stability of the system or construct [18, 19, 20]. Figure 5 shows the contour plot of displacement distribution for the bone and plates. From the figure, it can be illustrated that the tibia bone with Locking Compression Plate have the peak displacement of 0.98 mm and 0.26 mm at the fracture site. Meanwhile for tibia bone with Dynamic Compression Plate, it has the peak displacement of 1.53mm and 0.4 mm at the fracture site. Surprisingly, the displacement of Dynamic compression plate is at 50% higher than locking compression plate.

On the other hand, the plates were experienced with deformed and displaced shape during the high axial loading force. For Locking Compression Plate, the displacement is at 0.44 mm while Dynamic Compression Plate have a displacement of 0.66 mm. These data as well shows that DCP have 50% higher displacement compared to LCP. Figure 6 shows a bar graph represent the relativity of displacement in bone-plate system in LCP and DCP system.

It should be noted that the Dynamic Compression Plate has achieved compression at the fracture site by implementing compression screws from both fragments of the fracture. Other screws were inserted with a reason to provide additional stability along the bone plate interface. Subsequently, this technique is affective on simple fractures and only suitable for primary bone healing [23]. The Locking Compression Plate is introduced enable locking of screws head to the plate hole, thus allowing a more angle stable device. The aim of this design is to address multiple fragments in intraarticular fracture as well as providing a stable construct for fracture healing. The aimed of reduction techniques and minimally invasive plate insertion and fixation is to promote bone healing and prevents from non-union of the bone [23].

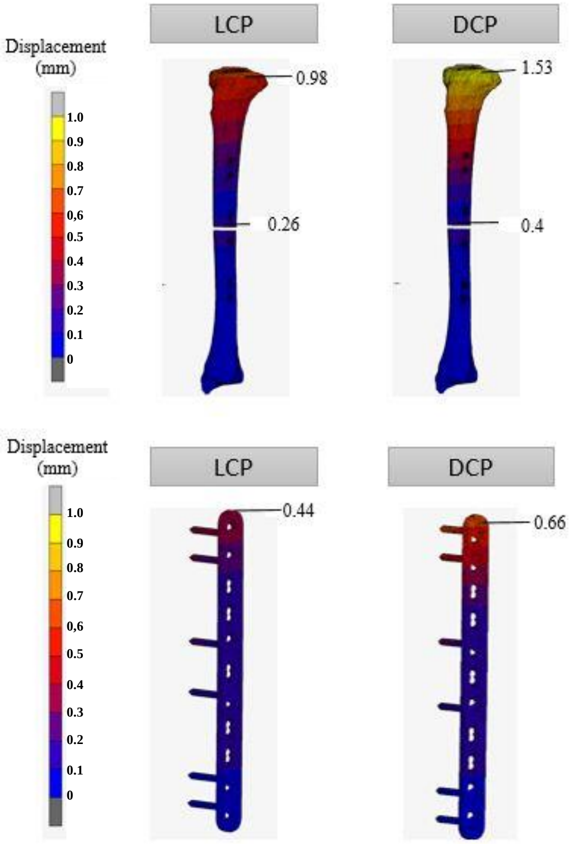


Figure 5 Contour plot of displacement distribution: a) Tibia bone with LCP plate, b) Tibia bone with DCP plate, c) LCP plate and d) DCP plate

From this recent study, it has been shown that the two plating techniques affects the bear stresses of the tibia bone upon the force load. In general, plate tend to have higher stress as the plate act as a stress shielding to the bone, taking up a large portion of loads rather than the underlying bone from high stiffness [24]. Both bones do not exceed the ultimate yield strength which is 193Mpa [18]. The successful simulation are shown in Figure 4. According to a study by Chung *et al.*, the stress distribution of a system could determine the stiffness of the model [24]. The lower the stiffness of the system, the more likely it is to deformed giving arise of risk that effect the bone loss. This as well shows that the strain in the bone decreases when the plate carried the most external load thus adequate amount of strain trigger healthy callus formation [24]. From the VMS result, the Dynamic Compression Plate have 45% higher than the Locking Compression Plate which is 232Mpa. This is exceeding the yield strength of stainless steel of 215Mpa in which could cause the plate to be deformed in its elastic state. This is very risky for the bone as the plate can cause non-union conditions to the bone [25].

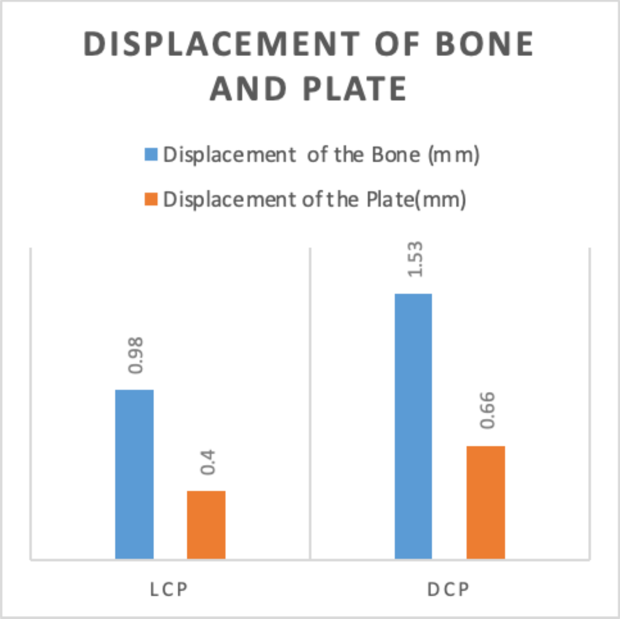


Figure 6 Displacement Magnitude of LCP and DCP models

According to Claes *et al*. in 2018, the range of interfragmentary motion that promote callus formation for bone healing at the fracture site are best at 0.1 to 0.6 mm. Their finding suggested that higher motion would delay union of the bone and disturb bone viability. The claims are well supported by Mehboob *et al*. in year of 2019 that interfragmentary motions at the bone are optimum from 0.1 to 1.0 mm to promote bone revascularizations and prevent healing complications [14], [26-27]. From our findings, the bone that fixed with Locking Compression Plate show the displacement value within those two abovementioned reported literatures. However, a precaution action should be made by medical surgeons if the Dynamic Compression Plate is their choices to treat patients since the displacement is higher than acceptable range.

4.0 CONCLUSIONS

Based on the finite element analysis, this study concludes that the LCP plate is more superior than DCP in terms of von Mises stress and displacement. The LCP demonstrated low stress and displacement that might help the bone to be always fixed in a position for a better healing process. The low values of stress and displacement is due to the rigidity of the construct where the placement of screws was near to the fracture site. Therefore, it is recommended that the placement of screws should be placed as near to the fracture as possible.

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