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Finite Element Analysis of Different Pin Diameter of External Fixator in Treating Tibia Fracture

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Abstract: Biomechanical perspective of external fixator is one of the biggest elements that should be considered in treating fracture bone. This is due to the mechanical behavior of the structure could be analyzed and optimized in order to avoid failure, increase bone fracture healing rate and prevents preterm screw loosening. There are three significant factors that affect the stability of external fixator and those are the placement of pin at the bone, configuration and components of external fixator. All these factors contribute to a question, what is the optimum pin diameter which exerts good stress distribution? To date, the research on the above-mentioned factors are limited in the literature. Therefore, this study was conducted to evaluate the unilateral external fixator with different pin sizes in treating tibia shaft fracture via the finite element method. First and foremost, the development of the tibia shaft fracture was conducted using Mimics software. The computed tomography (CT) data image was utilized to develop three-dimensional tibia bone followed by crafting fracture on the bone. Meanwhile, the unilateral external fixator was developed using SolidWorks software. In this study, five pin diameters (4.5, 5.0, 5.5, 6.0 and 6.5 mm) were developed and analyzed. Both tibia bone and external fixator were meshed in 3-matic software. Simulation of this configuration took place in a finite element software, Marc.Mentat. From the findings, it is shown that the larger diameter of pin demonstrated the lowest stress distribution. The size of the 5.5mm pin shows optimum diameter in terms of stress distribution with the value of 21.50 MPa in bone and 143.33 MPa in fixator. Meanwhile the displacement value of 1.42mm in bone and 1.20mm in fixator. In conclusion, it is suggested that the pin diameter of 5.5 mm is the most favorable option in treating tibia shaft fracture in terms of mechanical perspective.

Keywords: Finite element, pin diameter, external fixator, tibia shaft fracture

1. Introduction

A total of 85% of trauma patients are coming from limb injuries fractures especially for tibia and femur bone [1]. Among all bone injuries, tibia fracture contributes 8.1 percent to 37 percent of the statistics data per annum, in which makes them the most common injuries occur from an accident [2]. The reason why the tibia is the most vulnerable to

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injuries among other long bone is due to the properties of tibia itself as a subcutaneous bone [3]. To be noted, tibia fracture happened in both open and close fracture. An open fracture is a condition where the fracture is exposed to the outside environment after penetrating the skin. Fernandez Miguel A. et. al reported that open fracture incident happened with 11.5/105 cases reported in a year and 40% of them are lower-limb [1]. In clinical practice, treatments of open tibia fracture are very complex and require the cooperation from both orthopedic surgeons whom expert in bone and plastic surgeon whom expert in skin. In order to achieve fast healing and minimal infection rate, early fixation of the bone are crucial and must be done properly [4]. Whenever a fracture happened, the most important thing is to make sure the fracture is immobile where it can be obtained by using medical devices such as an external fixator [5]. The insertion of pins or wires together with other components of the external fixator into or through the bone is a method in fixating the fractured bone from moving [5]. Moreover, the external fixator is applied in a situation where damage soft tissues must be preserved and protect indirectly while providing support to bone fracture from mobile [6]. Apart from that, this system is a great alternative for an easy and low-cost application because the component assembled in this system remarks in maintaining the stiffness and stability of the fracture in bone [7]. There are a few configurations of external fixation which is uniplanar–unilateral, uniplanar–bilateral, biplanar and multiplanar and these types of configuration are being used in clinical nowadays [7]. Despite all the configurations of external fixator that can be found in the market, the configurations of each component in the external fixator are the most important. During the debridement process of injuries that will be followed by wound healing and annihilation of infection, a good configuration of the external fixator is needed in providing stable fixation of bone fracture [8].

Tibia is also known as subcutaneous bone, where it is located underneath the skin. This property of tibia makes them to easily break and vulnerable to trauma due to direct impact from the external environment. The fracture itself is very complex and frequently occurs in long bone fracture [3]. There are three main fractures occur in tibia; shaft fracture, plateau fracture, and plafond fracture. There are two types of fracture in bone; open fracture, and closed fracture. An open fracture results from a low-energy impact reported in the range of 3% to 6% while high-energy impact is reported around 12% to 56% [9]. The open fracture frequently accompanied by severe soft tissue damage which causes infection [10] and the rate of infection could be as high as 50% [1]. An external fixator is a medical device used to fix a fractured bone by providing support using pins and wire secured with external rod and stabilizes the fractured area [9]. Development and modification of external fixators have been made to increase the stability and reduce the complication involved during period of fracture healing. Apart from that, evolution of external fixator is due to the problem that becomes more complex over time. The problem mentioned is malunion, non-unions, and deformities of fracture bone [11, 12]. In the middle of the 20th century, Hoffman introduced a fixation device to support the long bone fracture. Since then, the external fixator becomes a popular fixation device used in the market [9]. There are three main concepts of external fixator in assuring a safe and effective usage; component of external fixator (pins and wires) should be safe when applied at area of interest, area of injuries can be accessed easily and these fixation devices have to fulfill biomechanical demand of both the patients and their injuries [9]. There are many types of external fixator applied in the medical field such as uniplanar–unilateral, uniplanar–bilateral, biplanar and multiplanar configurations. Stability is an aspect that could be defined as a total of contribution from both endoskeleton (bone fracture) and exoskeleton (external fixator) [13]. Different configurations of the external fixator will provide different stability that is suitable for a different type of fracture. Due to poor bone quality and small proximal bone fragment, Circular Hexapod External Fixation (CHEF) was selected to treat this patient's fracture instead of using open reduction and internal fixation (ORIF) system. After a few months, the patient could move independently and the knee range of motion improves between 0°-120° which could be considered as a successful treatment [14].

The main configuration that distinguishes unilateral external fixator with other fixator devices is the position of installation. The unilateral external fixator is installed at one side of the limb which provides the fractured bone with support and the functionality of the limb. There are two common configurations of unilateral external fixator; uniplanar-unilateral and uniplanar-bilateral fixator. Each configuration provides different mechanical properties, stability, and stiffness. Stability in unilateral external fixators can be enhanced by using large-diameter half pin installed in more points at bone fracture, the distance between the frame and the bone is reduced and the pin is placed out-of-plane [9]. Uniplanar - unilateral external fixators is the most suitable method to stabilize bone fracture [8]. In 2016, a comparative study between uniplanar unilateral external fixator and locking plate had been done. The study involves a total of 64 patients with open tibia fractures. The patients divided randomly into two groups by using Ranuni function (SAS software). One group of patients undergoes surgery to install traditional external fixator using 4.5 mm cortical or 6.5 mm cancellous Schanz pins, AO universal and transverse clamps and stainless-steel tubes while another group undergo surgery to install external fixation using supracutaneous plate application with 4.5 mm narrow locking compression plate and 4.5 mm cortical locking head screws. The main differences between both fixators are the components in which each of them constructs different configurations even though the application is for external only.

The concepts applied during installation of unilateral-uniplanar external fixators are the placement of pins which the pins are placed nearer and closer to the fractured site, the distance between lower pin and bone will be as lower as possible at minimum with only two bi-cortical Schnaz pins are installed. On the other hand, during the installation of the locking plate, the fixator will be placed as close as possible to the bone but still providing some space for the possibility of skin swelling during post-surgery and bi-cortical locked screw is preferable to be used in the locking compression plate. From previous study, a total of 64 patients were treated with a system named LEFS (Limb Extremity Functional Scale) in which shows the progress of patients by generating scores according to the focused aspects [8]. The higher the score, the lower the disability and the maximum score is up to 80. At the end of the study, all patients completed the follow up with a 100% union of bone. Unilateral-uniplanar external fixator requires 19.6 weeks to recover with 1 case of unacceptable angulation malunion while locking compression plate need 20.2 weeks to recover with 2 cases of unacceptable angulation malunion. However, unilateral–uniplanar external fixator records 6 patients suffer from soft tissue complications while locking compression plate records only 5 patients. This study shows that a unilateral-uniplanar external fixator is suitable for treating open fracture, but the locking compression plate is the way to substitute the traditional external fixator [8]. As far as author concerns, there is limited study on the pin sizes of external fixator. Therefore, this study was aimed to find out the most optimum pin diameter used in the external fixator using Finite Element Model (FEM). The results obtained in this study will be helpful in guiding the surgeons and medical practitioners to get the best outcome from external fixator installation.

2. Materials and Method

2.1 Development of Tibia Bone

A three-dimensional image of tibia bone as shown in figure 1 was obtained via Computed Tomography (CT) image resources from Hospital Tunku Ampuan Afzan, Pahang [15]. In this study, CT image of 22 years old male with body weight of 80 kg was used to develop a three-dimensional tibia bone model. To differentiate between cortical bone and other tissue in the images, a Hounsfield unit (HU) of 226 was set in Mimics software. Semi-automatic segmentation process with tools of delete and insert were utilized in this development process of 3D model. Noises from the CT images were removed manually in order to obtain a correct geometry of tibia bone. During the process of tibia bone development, a real bone was referred to accurately develop the tibia bone structure. The 3D model of tibia bone was then saved as STL format for next procedure.

Fig. 1 - Tibia bone after thresholding

2.2 Development of External Fixator

A unilateral external fixator was reversely designed via Computer-Aided Design (CAD) software; SolidWorks. The small components of the external fixator such as pin, rod and clamp were designed separately before proceed with next steps [16]. The rod of external fixator was modelled with a specification of 11 mm diameter and 170 mm in length [17]. Dimensions of 4.5 mm, 5.0 mm, 5.5 mm, 6.0 mm and 6.5 mm was used as pin diameters to fulfil the objective of this study [12, 18]. Then, every pieces of the component were assembled in SolidWorks by assuming glue conditions as shown in Figure 2 [18] and converted into a single body. Finally, the external fixator was meshed with a size of 1.5 mm and converted into STL format.

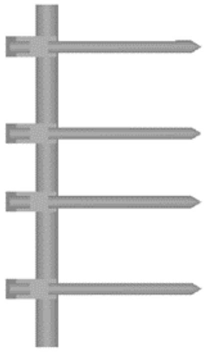

Fig. 2 - Unilateral external fixator developed using SolidWorks

2.3 Virtual Surgery

A virtual surgery was conducted in Mimics software in which to combine the external fixator and bone together. With a distance of 40 mm between rod and tibia, the external fixator was place to the bone where the rod and pin was in parallel and tangential position to the tibia bone [12]. This step followed by converting the configuration into the STL format. Another modelling software, 3-matic was used to create pinholes at the interface of pin and tibia bone. After holes have been made, both tibia and fixator were saved as volume mesh. Figure 3 shows the complete model of external fixator fitted to the tibia bone.

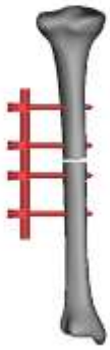

Fig. 3 - Installation of external fixator into the tibia bone

2.4 Finite Element Analysis

It is well known that finite element (FE) analysis could provide an internal stress analysis in which a simple assumption is needed to keep it under control [19]. Therefore, this study utilised FE method to analyse the external fixator. In this study, the FE model of bone and external fixator were assumed as linear elastic, isotropic and homogenous properties. For the external fixator, it was assigned with a Young's modulus of 110 GPa and Poison's ratio of 0.3 as a titanium alloys material [20]. Meanwhile, for the tibia bone, it was assigned with 7300 MPa and 0.3 for its Young's modulus and Poison ratio, respectively [15]. For the boundary condition, the distal part of tibia bone was fixed in all degree of freedom. Meanwhile, a total of 60% and 40% of total load (400N) was applied to the medial and lateral of proximal tibia, respectively. The amount of 400N is divided based on 60% and 40% portion and the respective load was used to calculate the stress at the respective area using the formula; P=F/A [21]. Mesh convergence study have been conducted in the previous study where five models of tibia bone and external fixator with different mesh sizes have been evaluated via h-refinement method [15]. It is found that the tibia and external fixator model was converged at 3.00 mm and 1 mm size, respectively. Therefore, this mesh size was used in this study. Apart from it, a validation study has been conducted in the previous study, in which a synthetic bone was used to validate the finite element model [22]. From the results, it is demonstrated that the FE model was validated.

3. Results and Discussion

Figure 4 shows the contour plot of displacement of the bone. From the overall picture, the bone starts to displace at the proximal region where the maximum displacement was found nearly to the fracture gap. It illustrated that the highest maximum displacement found at the external fixator with 6.0 mm pin size as compared to other four different sizes. The lowest displacement was demonstrated at model 3, where the pin size is 5.5 mm.

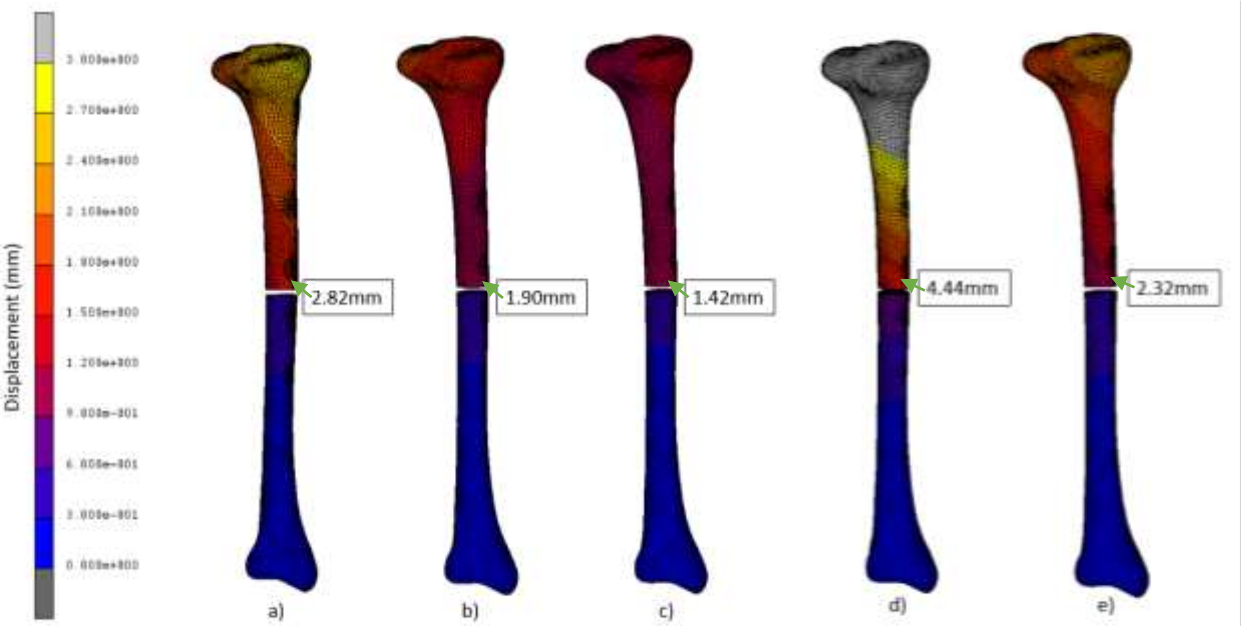

Fig. 4 - Contour plot of displacement at the fracture site of tibia bone with pin sizes of a) 4.5, b) 5.0, c) 5.5, d) 6.0, and e) 6.5 mm

Table 1 illustrating the peak von Mises stress of both bone and external fixator construct. It should be noted that the results obtained from the table were at the pin-bone interface. In general, the larger pin diameter demonstrated lower stress at the interface. The size of 4.5 mm pin diameter shows the highest von Mises stress (30.1824 MPa) and 202.014 MPa at the bone and external fixator, respectively. From other view, the lowest stress was found at the pin size of 6.5 mm. However, in taking consideration between displacement and stress distribution, the pin size of 5.5 mm is expected to be the optimum configuration where the stresses are still below the yield strength of bone (193 MPa) and titanium alloys (800-900 MPa). Apart from that, 5.0mm pin diameter results in 26.0595 MPa in bone and 160.748 MPa in external fixator which show lower stress distribution than 5.5mm pin diameter.

Table 1 - Peak von Mises stress for tibia and external fixator

No.	Diameter of pin (mm)	Peak Stress (MPa)	
		Tibia bone	External Fixator
1	4.5	30.1824	202.014
2	5.0	26.0595	160.748
3	5.5	21.4979	143.331
4	6.0	18.4173	129.126
5	6.5	17.2388	109.909

Maximum displacement for five different diameters of pins in tibia bone is illustrated in Figure 5. In general, the external fixator starts to deform at the proximal region. From other view, it shows that the highest maximum displacement (2.17 mm) occurred at the configuration 3 in which the external fixator consists of 6.0 mm pin size. Meanwhile, for the lowest displacement was found at the configuration 2 that fitted with pin diameter of 5.0 mm.

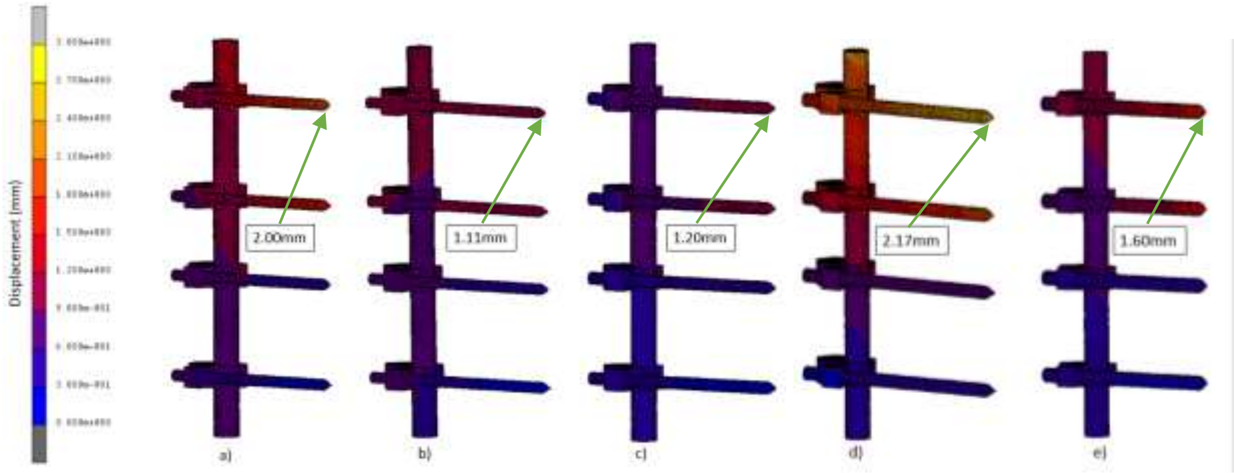

Fig. 5 - Contour plot of displacement for external fixator with pin sizes of a) 4.5, b) 5.0, c) 5.5, d) 6.0, and e) 6.5 mm

From the findings, 5.5mm pin diameter is the most favourable one. Pin diameter of 4.5mm and 5.5mm possess a high stress which will affect the stability of configuration while 6.5mm and 6.0mm have the largest area of pin diameter which then results in a slower healing process. It has been proved by clinical study where bigger size of hole will slowing the rate of healing process [23]. The 5.5mm pin diameter has the average stress distribution and pin diameter which make it the most favourable option for fixator configuration. Apart from that, all the configurations exert stress which is much lower than the ultimate strength for bone and fixator. The ultimate strength for bone is 193 MPa while for external fixator made up with Titanium is 800-900 MPa. However, the model 1 with pin size of 4.5 mm should be fully reconsidered if medical surgeons plan to utilize the configuration since the value of stress (202.014 MPa) at the bone site was more than yield strength of the bone (193 MPa). This would lead to bone fracture if patients are allowed to walk during intervention period. A summary of the findings for the von Mises stress and displacement at both bone and external fixator is illustrated in Figure 6 and 7, respectively.

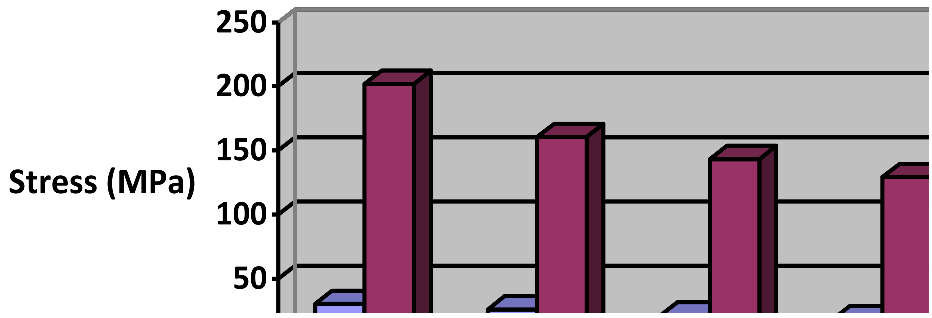

Fig. 6 - A bar chart of stress value at the bone and external fixator for all pin sizes

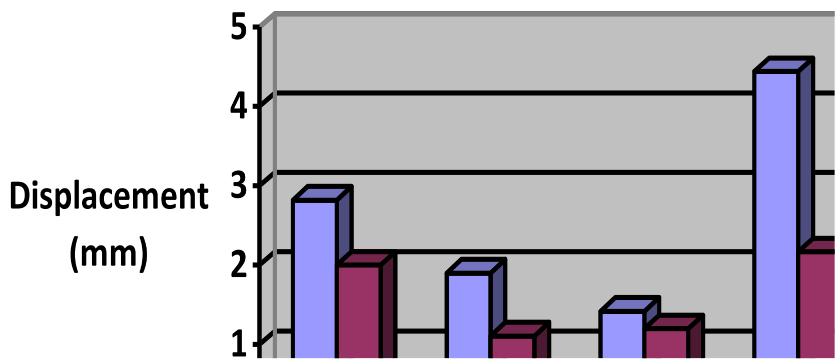

Fig. 7 - A bar chart of displacement at the bone and external fixator for all pin sizes

In this study, the FE analysis has some limitations due to computer resources and raw data from CT scanner. First, the tibia was developed as full cortical region even though the bone is composed with two layers of cortical and cancellous bone. For future study, it is recommended that finite element analysis can be done with considering the cortical and cancellous bone together in which could provide more reliable results and information. The properties of bone in another limitation where we assumed it as linear elastic, isotropic and homogenous. It should be noted that the real behaviour of human bone is anisotropic and inhomogeneous properties. Nevertheless, similar method have been utilized by many researchers with acceptable results by considering the complexity of 3D model [24-26].

4. Conclusion

This study was successfully conducted where the results of FE analysis predictions suggest the diameter of 5.5 mm pin can give a favourable result in terms of stress distribution and displacement. It produces with acceptable value of stress and displacement at both bone and external fixator. From here, it is hoped that the findings could provide a valuable information to medical surgeons to justify the choices of pin sizes in treating tibia fracture.

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