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Different Materials of Mitkovic External Fixator Influence the Stability and Stress Concentration of Open Subtalar Dislocation – A Finite Element Study

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ABSTRACT

Open subtalar dislocation is normally treated with an external fixator since this medical device can provide adequate stability, reduce the rate of infections, prevent deformity and promote fast healing process as compared to internal fixation. The stability of external fixator can be improved by using a different type of materials. Therefore, the present study simulated finite element model of open subtalar dislocation treated with Mitkovic external fixator with two different material properties; titanium alloy (Model 1) and stainless steel (Model 2). Ankle and foot bone were reconstructed using images of CT data taken from the previous study. Cartilages at the ankle joint were developed by offsetting the bone surfaces with 1 mm thickness while ligaments were modelled with linear links. Isotropic and homogeneous properties were assigned to the bone, Mooney-Rivlin model for cartilage and stiffness value for ligaments. An axial load of 350 N was applied to the proximal tibia to simulate stance phase of a gait cycle. The results of von Mises stress demonstrated that Model 2 has a low magnitude (127 MPa) at the pin-bone interface of tibia bone, compared with Model 1 (369 MPa). As for the local displacement at the bony segment of fibula, Model 2 (3.3 mm) indicated high stability of the external fixator than Model 1 (7.4 mm). In conclusion, the use of stainless steel material for Mitkovic external fixator can provide adequate stability and optimum stress distribution.

INTRODUCTION

Open subtalar dislocation can be defined as open injuries where the ligaments at the lateral side of ankle are torn. Previous scholar (Golner, Poletti et al. 1995) categorised it into four types; medial, lateral, posterior and anterior. The medial dislocations are the most common injuries where it is normally caused by the lateral displacement of the talus responding to an applied inversion force to the plantarflexed foot (Harris, Huffman et al. 2008).

The use of a medical device, called external fixator as a treatment of subtalar dislocation is popular amongst surgeons (Mitkovic, Bumbasirevic et al. 2005; Milenkovic, Mitkovic et al. 2006). This device can prevent complication such as infections, deformities and loss of reduction. In treating subtalar dislocations, many medical experts disallow full weight bearing for patients after a surgery (Harris, Huffman et al. 2008). However, this may cause in prolonged immobilization which can lead to deep vein thrombosis. Therefore, the external fixator is introduced since this device allows the early mobilization of patients and preventing complications while supporting the ankle joint for ligament healing (Ansah and Sella 2000). To date, the Mitkovic external fixator has becomes the most popular construct for treating open subtalar dislocations (Ansah and Sella 2000; Milenkovic, Mitkovic et al. 2006). This construct is based on unilateral external fixator with a system that provides three-dimensional freedom.

For treating open subtalar dislocation, stability of fixation and ankle joint is one of the main factors to ligament healing (Golner, Poletti et al. 1995; Carroll and Koman 2010). The stability of external fixator can be demonstrated by using a proper material (Ramlee, Abdul Kadir et al. 2014). Additionally, wrong selection of material can increase stresses and displacement at the pin-bone interface and distal fibula, respectively. Therefore, the objectives of the current study are to reconstruct three-dimensional ankle subtalar dislocation fixated with two different materials of Mitkovic external fixator and to investigate the effect of stress and displacement during the stance phase of a gait cycle.

MATERIALS AND METHOD

Modelling of Bone

CT data images of healthy person were used to reconstruct the three-dimensional (3D) model of eight bones which include metatarsals, cuneiforms, navicular, cuboid, calcaneus, talus, fibula and tibia bone (Ramlee, Abdul Kadir et al. 2014). Two different segments of bone were developed by setting a threshold value: more than 700 was for the cortical and less than 700 was for the cancellous. For a region of interest, the tibia and fibula were cut approximately 20 cm above the medial tibia malleolus. The 3D model of bones was saved in STL file for further pre-processing method. All of these steps were performed in Mimics 15.1 software (Materialise, Belgium).

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Modelling of Cartilage and Ligament

Articular surfaces of bones were extruded out with a uniform size of 1 mm. The 3D model of cartilage for calcaneus, talus, fibula and tibia were constructed via manual segmentation process (Ramlee, Abdul Kadir et al. 2014). This includes using Boolean operations in Mimics software to check whether there is any intersection between two different cartilages at a bone joint. Some modifications were conducted due to the intersection between two rigid bodies of cartilage and this was repeated until the intersecting numbers become zero. For the material properties, the cartilages were assigned with Mooney-Rivlin hyperelastic behaviour with coefficients of C_{01}=0.41 MPa and C_{10}=4.1 MPa. The complexity of the ankle and foot joint model (Figure 1) came with thirty-seven ligaments surrounding the tissue. The ligaments were modelled using linear link elements and the stiffness value were set ranging from 40 to 400 N/mm (Siegler, Block et al. 1988; Pfaeffle, Tomaino et al. 1996; Beumar, Van Hemert et al. 2003; Liacouras and Wayne 2007; Iaquinto and Wayne 2010; Ramlee, Abdul Kadir et al. 2014). The positions of ligaments were based on an anatomy book and confirmed by a medical expert (Netter 2003). Open subtalar dislocation was simulated with an assumption of non-existed ligaments at the lateral collateral side (Sloane and Coutts 1937; Fahey, J.J et al. 1965; D'Anca and A.F. 1971; Daruwella 1974). These ligaments are the calcaneofibular, posterior talofibular and anterior talofibular (Figure 2).

Finite Element Modelling

All STL files were then imported into Marc.Mentat (MSC.Software, USA) in order to convert the 3D model into linear first tetrahedral elements (Figure 2). A properties of 7300 MPa and Poisson's ration of 0.3 (Nakamura, Crowninshield et al. 1981) were assigned to the cortical bone while the material properties of cancellous bone were set to 1100 MPa and 0.3 (Kim, Kim et al. 2011). The Mitkovic external fixator was modelled via Solidworks software (Dassault, USA) with rods and pins size of 11 mm and 5 mm, respectively. The fixator then meshed with linear first order tetrahedral elements using 3-Matic 7.1 (Materialise, Belgium). Two pins were fixated at the tibia, one at the calcaneus and another pin at the first metatarsal bone to represent the Mitkovic construct as shown in Figure 1. In the present study, two different material properties of external fixator were used; Model 1 was developed using the Mitkovic titanium alloy and Model 2 was developed using the Mitkovic stainless steel. These two models have Young's modulus of 110,000 MPa (Benli, Aksoy et al. 2008) and 200,000 MPa (Vasquez, Pedersen et al. 2003), respectively. A convergence study was conducted in the previous study (Ramlee, Abdul Kadir et al. 2014) and the findings showed that optimum mesh size for the bone was 3 mm and the external fixator was 1 mm.

Boundary Conditions

An axial load was applied to the proximal tibia bone. The load was based on a force taken from the gastrocnemius and soleus muscles during the stance phase. During stance phase of a gait cycle, 50% of the body weight was generated (Simkin 1982; Cheung, M. et al. 2005). In the present study, 350 N was applied based on the subject's body weight of 70 kg. For preventing a movement of the rigid body during the simulated condition, all metatarsals and calcaneus bone were fixed.

RESULTS AND DISCUSSION

Von Mises Stress

Figure 3 shows the contour plots of von Mises stress at the pin-bone interface for tibia, calcaneus and metatarsal bone during the stance phase of a gait cycle. The maximum stress at Model 1 (369 MPa) is greater than Model 2 (127 MPa) with at least 90% difference between both models at the second cortex of pin-bone interface. For the calcaneus bone, Model 1 (683 MPa) produced at least 2.9 times greater stress compared to Model 2 (262 MPa). On the other hand, the von Mises stress at the pin-bone interface of metatarsal bone for Model 1 (591 MPa) demonstrated larger magnitude than Model 2 (245 MPa), with 82% difference between both models. In this study, the stress concentrated at the pin-bone interface was in agreement with previous studies(Brianza, Brighenti et al. 2011; Donaldson, Pankaj et al. 2012). The high stresses at this critical local point supported the decision made by medical surgeons for disallowing patients to experience full weight bearing in clinical practice (Ansah and Sella 2000; Harris, Huffman et al. 2008; Dlimi, Mahfoud et al. 2011). It is cruciate to note that a normal bone can sustain an axial load until the ultimate strength of 193 MPa (Pinner and Sangeorzan 2001). Based on the results of the von Mises stress in the present study, it is not recommended for patients to walk and stand during treatment period.

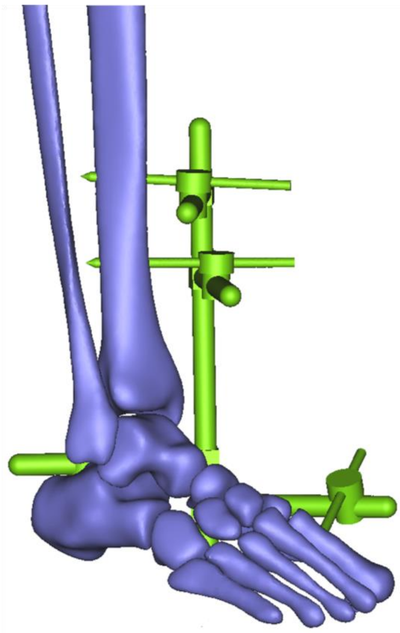

Fig. 1 Three-Dimensional model of ankle and foot bone fixated with Mitkovic external fixator

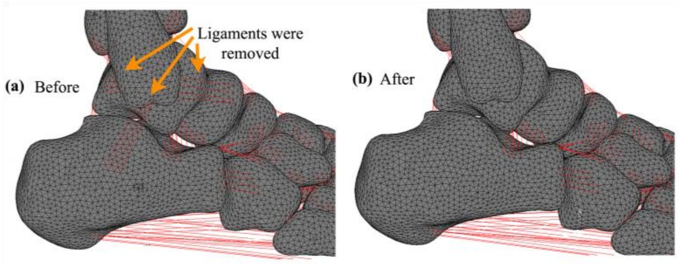

Fig. 2 Finite element model showing the ligaments were removed to simulate open subtalar dislocation

Contour plots of von Mises stress of external fixators with different material properties from numerical simulation are shown in Figure 4. The stress concentrated more in Model 2 (524 MPa) at the calcaneus pin as compared to Model 1 (486 MPa). However, these peak values are still below the ultimate strength of titanium alloy (500-600 MPa) and stainless steel (800-900 MPa)(Gorsse and Miracle 2003; Hyde, Sun et al. 2010).From another view, the stress is also distributed at connecting bar, tibia pin and first metatarsal pin. Nevertheless, the stresses surrounding external fixator were below the peak values, which indicates that the Mitkovic frame is safe to be used for treating this particular pathological problem.

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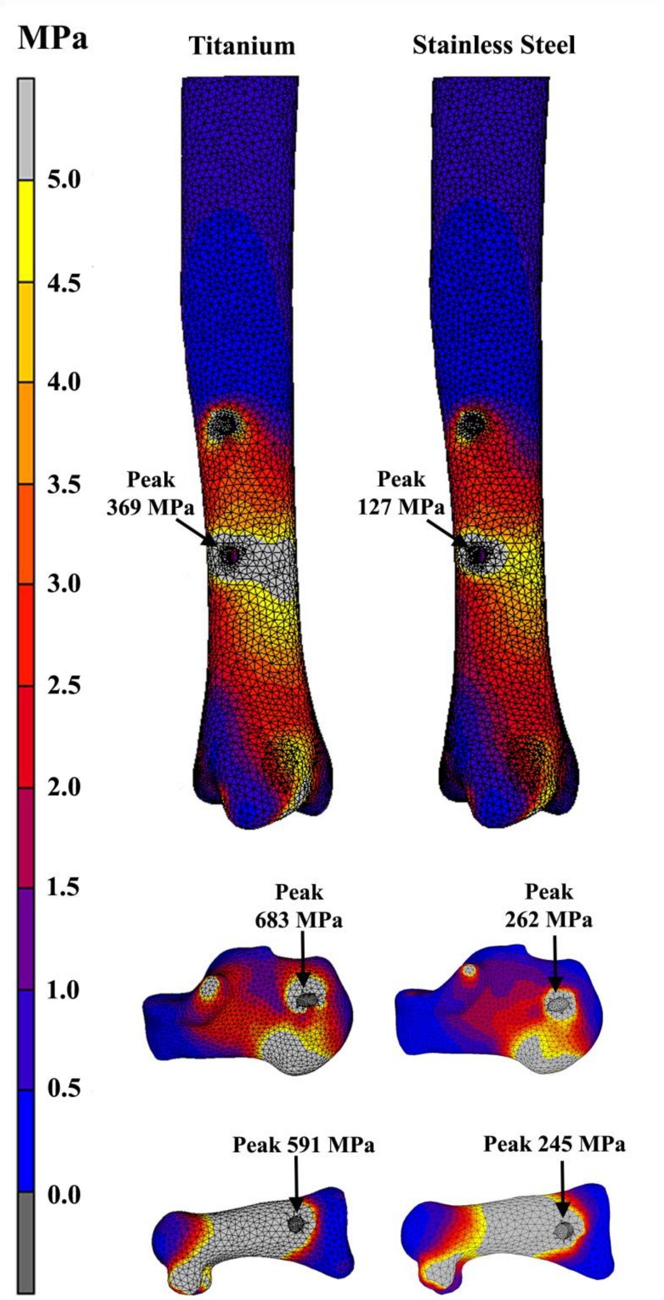

Fig. 3 Von Mises stress at the pin-bone interface

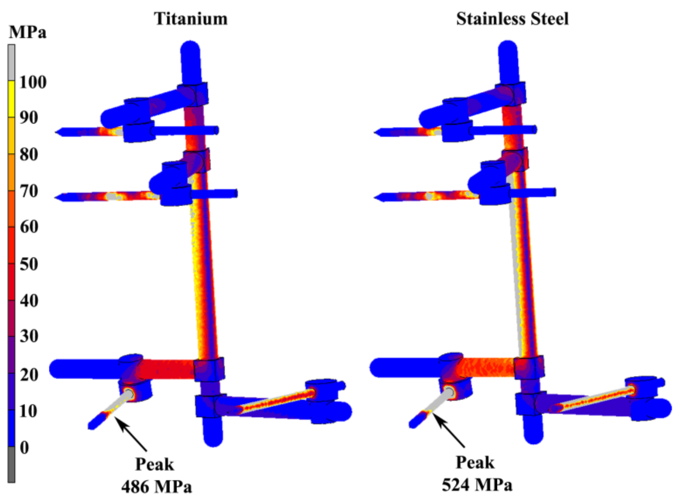

Fig. 4 Contour plots of von Mises stress of Mitkovic external fixator

Displacement

Local displacement at the bony segments that are connected by calcaneofibular ligament as shown in Figure 5. Model 1 with material of titanium alloy demonstrated higher displacement of 7.4 mm as compared to Model 2 (3.3 mm). To be noted, the stability of the bone affected the healing process of ligaments. With higher magnitude of displacement, a time taken for ligaments to heal will be longer. Previous studies demonstrated the same situtation where the smaller displacement at the bony segment of ankle joint can minimize the time taken remove external fixator (Golner, Poletti et al. 1995; Ansah and Sella 2000; Ramlee, Abdul Kadir et al. 2014; Ramlee, Abdul Kadir et al. 2014).

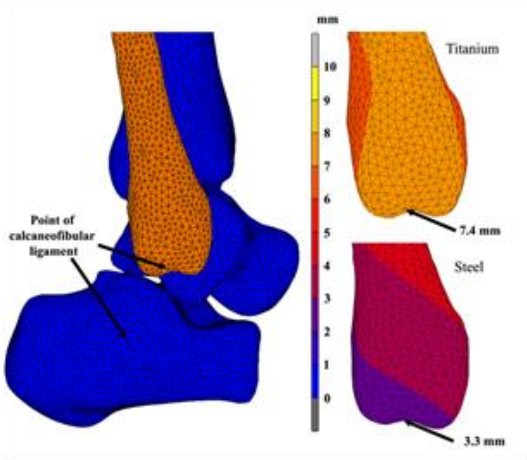

Fig. 5 Contour plots of displacement at the local point of calcaneofibular ligaments

External fixator is a favourable option for the management of open subtalar dislocation due to its minimally invasive property, able to provide adequate stabilization and less infection (Pinner and Sangeorzan 2001; Seibert, Fankhauser et al. 2003). Many scholars proved that stable fixation can hasten soft tissue healing during a treatment (Seibert, Fankhauser et al. 2003; Chandran, Puttaswamaiah et al. 2006). A proper strategy should be taken properly by medical surgeons before a surgery can be made. One of the strategy is the selection of material of external fixator. Inability to provide a stable construct due to improper selection of material is the major cause of post surgery complications such as mal-union, non-union, and secondary fracture at the pin-bone interface (Inokuchi, Hashimoto et al. 1996; Vasquez, Pedersen et al. 2004). Based on the results from Figure 3, the secondary fracture could be happened at the pin-bone interface of tibia, calcaneus and first metatarsal bone if the medical doctors allowing the patients to walk and stand during the treatment period.

Several assumptions and limitationswere considered in the present study where these cannot be avoided when dealing with computational simulation. First, the geometrical condition of open subtalar dislocation was simplified and followed a normal patient condition. Though the dislocation can cause talus or calcaneus bone to be displaced from original position, however, the effect of these bones can only be simulated by using high resources of computer as well as CT data images from real patients. Nevertheless, the simulated of open dislocation and fracture bone were demonstrated by previous studies with an acceptable outcomes (Ezquerro, Jimenez et al. 2007; Benli, Aksoy et al. 2008; Brianza, Brighenti et al. 2011; Izaham, Kadir et al. 2012). The second limitations of the study was the assumption of linear isotropic and homogenous for both cortical and cancellous bone. To be noted, this limitation and assumption were normally used by the biomedical engineers and researcher to simulate the bone properties via finite element method (Liacouras and Wayne 2007; Izaham, Kadir et al. 2012; Liu and Zhang 2013). Therefore, it is

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recommended that future investigation can be performed using greyscale value of CT images to mimick real material properties of the bone.

Another limitation in this study is the axial loading. A force value applied at the proximal tibia was simulated from Achilles tendon force during the stance phase of a gait cycle(Simkin 1982), while the other structural muscles such as longus and brevis were not considered in this study due to its low magnitude of forces. In addition, the thickness of cartilages was another assumption where a uniform thickness of 1 mm were applied only for tibia, fibula, calcaneus and talus bone (Ramlee, Abdul Kadir et al. 2014). The rest ofcartilages around foot should be constructed in the future studies where this could influence the simulated results.

CONCLUSION

The present study simulated finite element model of open subtalar dislocation treated with Mitkovic external fixator with two different materials; titanium alloy and stainless steel. As compared with titanium alloy,the results obtained in terms of stress and displacement demonstrated that stainless steel material for the external fixator can provide adequate stability to the bony fragment as well as optimum stress surrounding bone tissue. However, extra care should be considered when allowing patients to walk and stand during the treatment to avoid complications especially secondary fracture at the pin-bone interface.

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