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Original Article

Three dimensional finite-element analysis of treating Vancouver B1 periprosthetic femoral fractures with three kinds of internal fixation

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Abstract: This study is to compare the stress distribution, maximum stress, stiffness and relative displacement of 3 different models of Vancouver type B1 fractures fixed with 3 kinds of internal fixation using finite element analysis. FINITE ELEMENT MODELS OF periprosthetic femoral fractures were reconstructed and fixed with 3 kinds of internal fixations. The internal fixations included double circle cable, traditional locking titanium plate and multidirectional locking plate of double-row screws, designed by the authors. Through establishing finite element models of Vancouver type B1 fractures, axial compression and torsion were simulated on different fixations. The von-Mises stress and total deformation distribution of femur, internal fixators and the fracture sites were investigated. Finite element analysis was performed for B1 periprosthetic fractures in both normal bone and osteoporosis models. Compared with double circle cable and traditional locking titanium plate of single-row screws, multidirectional locking plate device had higher stiffness, more even stress distribution and better stability under the same vertical and rotational loading. Smaller relative deformation and smaller maximum stress of prosthesis and fixation were found in the multidirectional locking plate system, which suggested that it is a more stable and stronger device than double circle cable and traditional locking titanium plate for Vancouver type B1 periprosthetic fractures. The multidirectional locking plate system is more stable and stronger than double circle cable and traditional locking titanium plate. It is expected to be an effective device in treating Vancouver type B1 fractures.

Keywords: Femur, periprosthetic femoral fracture, finite element analysis, internal fixation, Vancouver classification

Introduction

Total hip arthroplasty (THA) is an extremely effective procedure in relieving pain and dysfunction for patients with hip joint cartilage degeneration, femoral head necrosis and femoral fractures [1]. Periprosthetic femoral fractures (PFF) can occur following THA and are expected to increase because of the escalating number of hip joint replacements in treating bone disease and fractures [2]. Firstly described by Duncan and Masri, the Vancouver classification has been widely used to classify PFF according to the location of the fracture, the stability of the implant, and the quality of the remaining bone [3]. It has been considered as gold standard in evaluating PFF on the femoral side.

Vancouver type B1 fractures are those occurring at the tip of the THA stem in which the hip implant is stable [4]. Management of these fractures remains a surgical challenge due to the presence of the underlying prosthesis. Current treatment algorithms generally recommend open reduction and internal fixation (ORIF) for this type of fractures [4]. Available fixations include single cerclage wire or screw, double circle cable or titanium cerclage cable, single column locking plate, plate-cable system, and allogeneic cortical bone plate [5]. However, there is no gold standard in treating Vancouver type B1 fractures despite various randomized controlled clinical trials with regard to different internal fixations. Besides, it has not been extensively investigated on the char-

Table 1. Material properties of bones and implants.

Material	Elastic Modulus (MPa)	Poisson's Ratio	Reference
Bones			
Normal			
Cortical Shell	12,400	0.30	
Cancellous Core	104	0.30	
Osteoporosis			[10]
Cortical Shell	8308	0.30	
Cancellous Core	35.36	0.30	
Implants			
Fixators	110,000	0.30	
Prostheses	210,000	0.30	

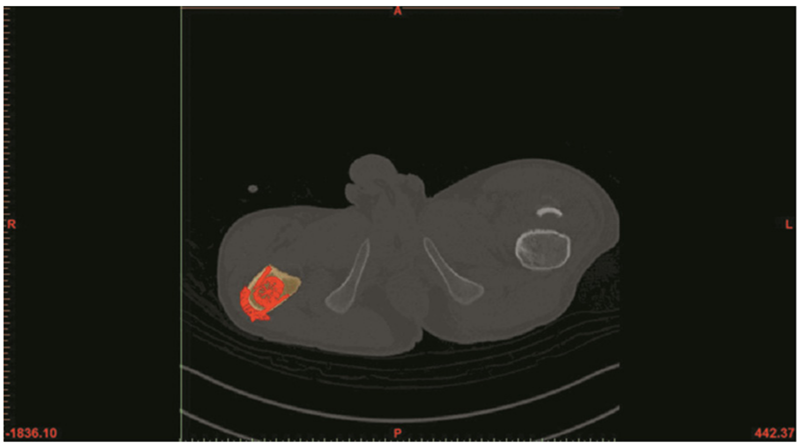

Figure 1. Illustration of multidirectional locking titanium model. The red part was the prosthesis and titanium screws.

acteristics of type B1 PFF, the stress distribution and mechanical stability of different internal fixations.

As an effective and accurate numerical method in studying irregular objects, finite element analysis (FEA) provides orthopedics or other specialists with suggestions on clinical treatment through computational models. These models based on the finite element (FE) method make it possible to assess the full pattern of strain and stress distribution. Such investigation can lead towards the optimum biomechanical management of PFF [6].

In this study, an FE model of PFF fixation was used to examine the biomechanical performance of three different PFF fixation methods for Vancouver type B1 fractures in normal and osteoporotic bone. Single cerclage wire and screw were not investigated in this study because of their demonstrated high failure rate in treating type B1 fracture [5]. And the cable-plate system will not be discussed here due to the biomechanical condition limits. Double circle cable fixation and traditional locking titanium plate system are most commonly used methods in type B1 fracture [7]. Suggested by a latest biomechanical research, tangential bicortical screw fixation may offer more optimal stability than cable-plate systems when using a plate applied laterally on the femur [8]. Therefore, the included fixations were double circle cable, traditional locking titanium plate and multidirectional locking plate of double-row screws, a kind of bicortical screw fixation, designed by the author.

The quality of the remaining bone is closely related to the success of PFF treatment and osteoporosis is a demonstrated predisposing factor in PFF [9]. Therefore it is essential to carry out a comparative study between normal bone and osteoporosis on different internal fixations.

The stress distribution, stiffness, maximum stress and relative displacement were compared under the same vertical and rotational loading using FEA. This study was aimed to provide new internal fixation device for Vancouver type B1 fracture by analyzing biomechanical characteristics of different internal fixations.

Materials and methods

Model development

This study was approved by the ethics review board of Shandong University. Informed consent was obtained from the volunteer. The CT image dataset was obtained by scanning the lower limb of a single 24-year-old male volun-

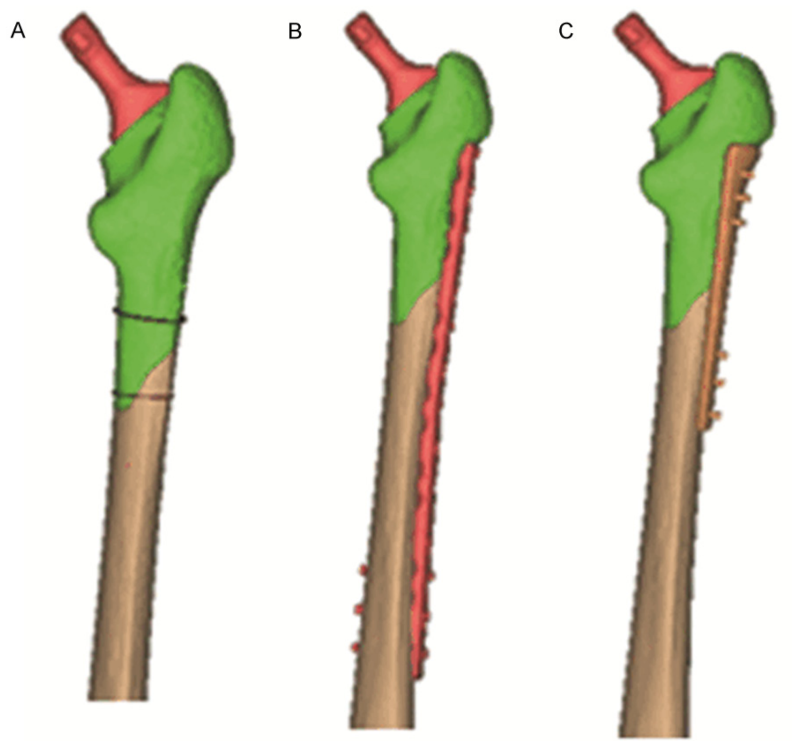

Figure 2. Three kinds of finite element model. A. Double circle cable internal fixation model. B. Traditional locking titanium plate internal fixation model. C. Multi-directional locking plate internal fixation model.

Table 2. Elements and nodes in the finite element models of three internal fixations

	Elements	Nodes
Implant	33406	8826
Bone	132249	34288
Double circle cable (a)	1845	982
Locking plate (b)	106103	25712
Multi-directional locking plate (c)	55807	14709

teer, with a weight of 75 kg and a height of 176 cm. Prior to CT scanning, X-ray was performed to ensure that the subject was free of pathology. The CT protocol is summarized in **Table 1**. The total femoral length was 412 mm measured from the femoral head center to the distal femoral intercondylar line.

The dataset was conducted for creating the finite element model in the DICOM (Digital Imaging and Communications in Medicine) format. Using 3D model reconstruction software (MIMICS 15.0, Materialise, Leuven, Belgium), a femoral model was developed and exported in the. stl format. Osteotomies and joint replacements were performed as real arthroplasty surgery. The LCU prosthesis was provided by the manufacturer (Waldemar Link, Hamburg, Germany). Type B1 fracture was simulated through the software and the model was then transported and polished in Geomagic Studio software 10.0. The IGES format files were saved and transported to Solid Works 2013 (Dassault Systemes, MA, USA).

The multidirectional locking plate system, one of the tested internal fixation devices in this study, was created by the authors. Originated from Non-Contact-Bridging-plate (NCB), multidirectional locking plate was attached to the tension side of the femur and the double-row screws penetrated the implant and femur cortex in multiple directions with a angle less than 30° (**Figure 1**). The Vancouver type B1 model and the fixation devices were assembled in Solid Works (**Figure 2**).

Analysis by FEA

Each model was then exported to a finite element package (ABAQUS v. 6.13, Dassault Systemes, MA, USA) for analysis. The severity of osteoporosis differs between patients and the finite model based on CT scanning on osteoporosis patients will be lack of accuracy. The finite element model of Vancouver type B1 fracture in osteoporosis group can be constructed through changing the material properties using the software, which has been demonstrated by Turner AW [10]. The material properties of the bones and implants were assumed to be isotropic and linearly elastic, as shown in **Table 1**. A friction contact was defined to represent the fracture site. A fixed boundary condition was applied to the screw-plate interface and the screw-bone interface. The element size and number of elements were shown in **Table 2**.

Table 3. Comparative results of different internal fixations under the same loading in normal bone group

Loading mode	Axial compression				Torsion			
Group	Control	Double circle cable (a)	Locking plate (b)	Multi-directional locking plate (c)	Control	Double circle cable (a)	Locking plate (b)	Multi-directional locking plate (c)
Mean stiffness (N/mm)	257.2899	168.3502	262.9273	265.4867	16.49747	11.13954	17.64944	22.12103
Implant maximum stress (Mpa)	94.46	137.348	144.447	63.198	71.304	24.444	7.828	15.897
Fixation maximum stress (Mpa)	-	776.156	382.217	153.418	-	154.833	194.302	61.817
Maximum fracture movement (mm)	-	0.084	0.170	0.019	-	0.104	0.320	0.022

Table 4. Comparative results of different internal fixations under the same loading in osteoporosis group

Loading mode	Axial compression				Torsion			
Group	Control	Double circle cable (a)	Locking plate (b)	Multi-directional locking plate (c)	Control	Double circle cable (a)	Locking plate (b)	Multi-directional locking plate (c)
Mean stiffness (N/mm)	165.0165017	112.5703565	196.7213115	176.7825575	9.216266944	6.898113615	13.11579327	13.99503778
Implant maximum stress (Mpa)	124.733	139.776	148.46	81.574	92.723	27.298	8.165	18.737
Fixation maximum stress (Mpa)	-	958.801	346.872	170.454	-	198.891	168.775	74.028
Maximum fracture movement (mm)	-	0.117	0.205	0.029	-	0.126	0.375	0.021

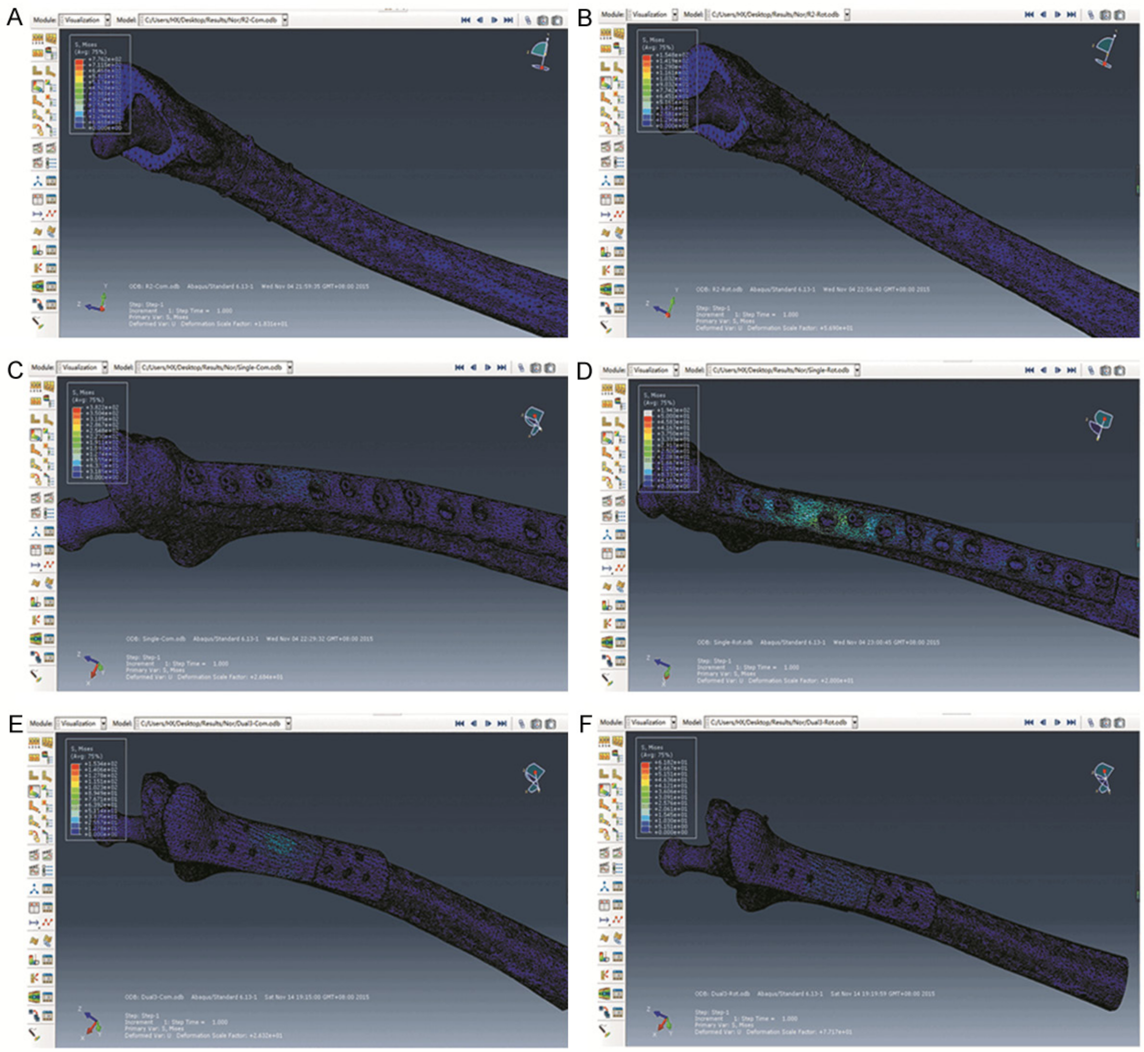

Figure 3. Stress distribution of axial compression and torsion by different internal fixation methods on normal bone. A. Stress distribution of axial compression by double circle cable internal fixation. B. Stress distribution of torsion by double circle cable internal fixation. C. Stress distribution of axial compression by traditional locking titanium plate internal fixation. D. Stress distribution of torsion by traditional locking titanium plate internal fixation. E. Stress distribution of axial compression by multi-directional locking plate internal fixation. F. Stress distribution of torsion by multi-directional locking plate internal fixation.

It was assumed that the bone was completely broken and the fracture sites were in entire contact. All nodes of the femoral medial and lateral condyle were fully constrained. An axial load of 500 N was applied perpendicularly to the interface of femoral head and acetabulum in an axially downward direction. For rotation, a 7-Nm torque was applied to the proximal femur and the surface nodes of the distal femur were fully constrained [11].

Stiffness of internal fixations, stress distribution and maximum stress of both fixations and femur, relative displacement and peak values were determined in three fixation devices for both groups.

Results

Compare with double circle cable fixation and traditional locking titanium plate method, the multidirectional locking plate had a higher stiffness and better stability under the same vertical and rotational loading. The stress was distributed in a more even manner, and the maximum stress on the implant and internal

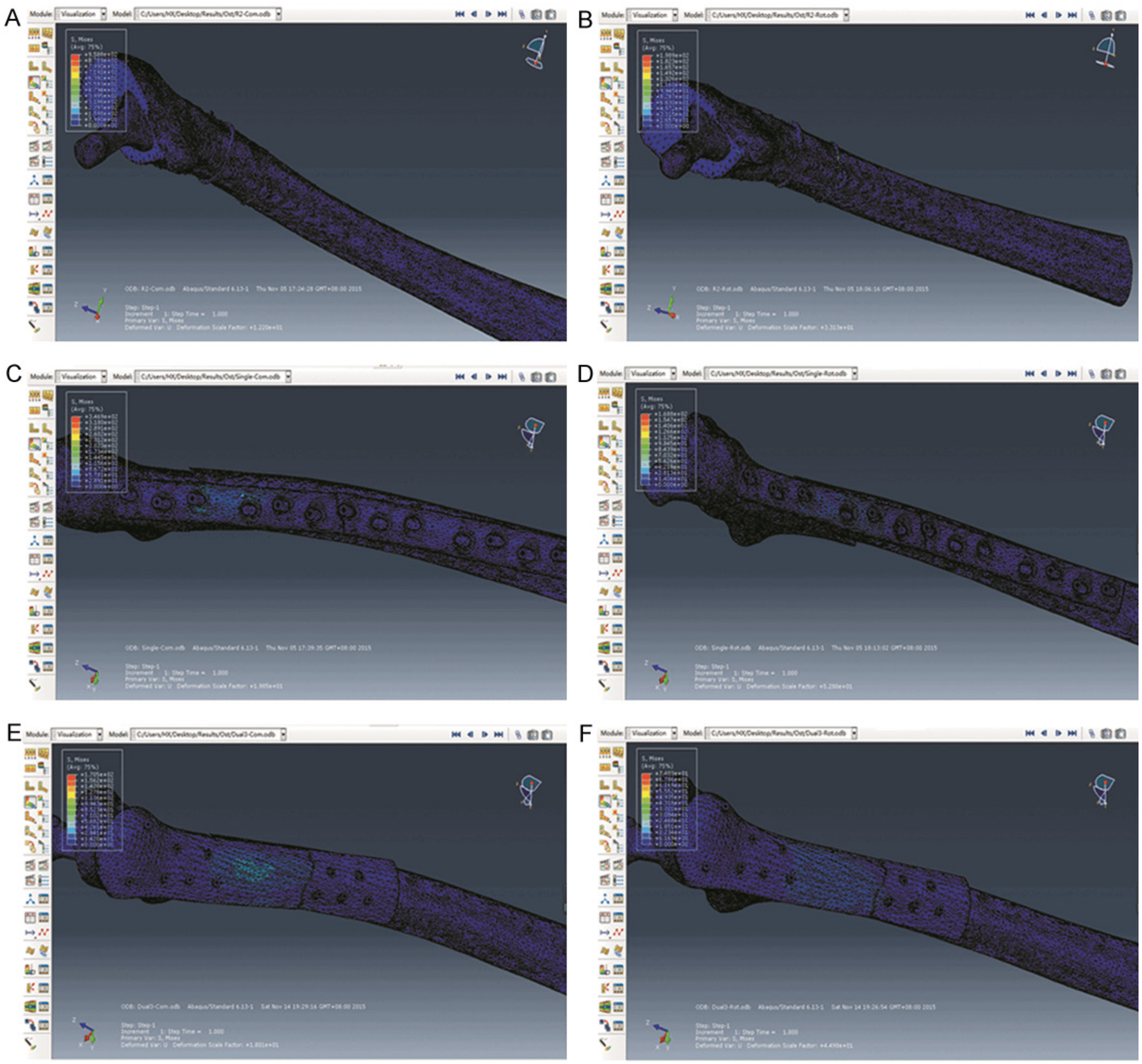

Figure 4. Stress distribution of axial compression and torsion by different internal fixation methods on osteoporosis bone. A. Stress distribution of axial compression by double circle cable internal fixation. B. Stress distribution of torsion by double circle cable internal fixation. C. Stress distribution of axial compression by traditional locking titanium plate internal fixation. D. Stress distribution of torsion by traditional locking titanium plate internal fixation. E. Stress distribution of axial compression by multi-directional locking plate internal fixation. F. Stress distribution of torsion by multi-directional locking plate internal fixation.

fixation was lower. The incidence of the internal fixation breakdown and refracture would be lower.

The data was shown in details in **Tables 3** and **4**. A higher stiffness means better stability, and a higher maximum stress on the implant and internal fixation means an increased incidence of internal fixation loosening, breakdown and refracture. A higher maximum displacement of the fracture sites indicates a more unstable fracture.

The stress distributions of different internal fixations were presented in **Figures 3** and **4**. The stress was distributed most even in the multidirectional locking plate system under all loading conditions in different bone quality groups. The results revealed that the peak stress of different internal fixations concentrated on the fracture sites.

Discussion

PFF is one of the major complications after THA and has become the third cause of revision arthroplasties of hip [12]. The apparent increase in its prevalence has been attributed to the growing population of patients with existing hip arthroplasties, increasing elderly patients at risk of falls, and the increasing number of young active patients at risk of high-energy trauma events [13]. Treatment of PFF is always challenging considering the necessity of ORIF or revision arthroplasties. Vancouver type B1 fractures account for up to 1/3 of all periprosthetic femoral fractures [12].

The Swedish National Hip Joint Arthroplasty Registry Report (1979-2010) indicates that Vancouver type B fractures occupied 86% of 1049 periprosthetic femoral fractures (B1, 29%; B2, 53%; B3, 4%) [14]. ORIF is recommended for type B1 fractures as the implant is in steady state. A systemic review by Dehghan and Niloofar [15] on internal fixation in Vancouver type B1 fractures reveals that the union rate can reach 95% while the revision rate account for only 9% after ORIF.

Management of Vancouver type B1 fractures remains a surgical challenge due to the presence of the underlying prosthesis and the quality of the remaining bone. As a generally accepted risk factor, osteoporosis, which leads to decreased bone density and poor bone quality, may contribute to PFF [14]. Compared to normal bone, the pull-out strength and shearing strength decrease in osteoporosis [16]. Osteoporosis can greatly affect the initial stability acquired through ORIF [9]. Malunion, union and internal fixation break down are common complications after ORIF in PFF, and are caused mainly by damage to the femoral blood supply and changes in biomechanical performance of local sites [17]. It is of great importance to determine the biomechanical performance between normal and osteoporotic bone in different fixations.

First introduced in 1998 [18], polyaxial locking plates were used to treat fractures in the distal section of femur, proximal section of the humerus and tibial plateau later in 2003. This implant (Non-Contact-Bridging-plate) is equipped with anchoring device which allows a locking screw placement in a range of 30° to the plate level. Angular stability is achieved by fixing the head of the screw with an additional cap turned into the plate thread covering the screw head. The multidirectional locking plate system, one of the tested internal fixation devices in this study, was created by the authors. Originated from NCB, multidirectional locking plate is attached to the tension side of the femur and the double-row screws penetrated the implant and femur cortex in multiple directions with a angle less than 30°. This system can effectively distribute the stress and function well in preventing axial compression and torque. Double circle cable fixation and traditional locking plate were also determined on their biochemical performance as they were most commonly used method in Vancouver type B1 fractures.

Compared with the double circle cable method and traditional locking plate system, higher stiffness, more even stress distribution and better stability were detected in the multidirectional locking plate fixation devices under the same vertica land rotational loading in both normal bone and osteoporosis groups. The maximum stress and relative deformation in the multidirectional locking plate fixation were lower than the other devices in both groups, indicating a more stable and stronger internal fixation for Vancouver type B1 fractures.

One of the main limitations of this study is that the effects of soft tissue including muscle and ligament are not considered. This is because that the finite element model is a simplified one. It is impossible to achieve the complete attachment of the plate to the skeletal system and no gap in the fracture site in reality [19]. Another shortcoming is the application of the same loading conditions in one direction.

Disclosure of conflict of interest

None.

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