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Original Research Article

Biomechanical analysis of diversified screw arrangement on 11 holes locking compression plate considering time-varying properties of callus

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ABSTRACT

The 11 holes locking compression plate (LCP) is a type of fixator which is currently used in orthopedic surgeries for fixing fractures of long bones. 8 styles of screw positioning on this plate are possible so each orthopedist may use one of them during operations. The aim of the current study was the analysis of diversified screw arrangement on the mentioned LCP for fixation of medial transverse fracture of tibia considering time- varying properties of bone callus in 16-weeks curing duration. Stress shielding effects were also considered. Finite element method using Mimics 10.01, Solid works 2012 and Abaqus 6.11-1 software have been applied. Modeling of bone was done based on computer tomography (CT) scan of human right tibia and four types of forces have been loaded on intact bone and the same was loaded on fixated fractured ones in 8 treatments of fixation. Stresses in bone, plate and screws, also gap or callus strains and stiffnesses in 5 terms of curing duration in all of the treatments have been investigated and compared together using new defined parameters. Finally the preferred treatment was concluded. Results of this study may be used by orthopedists in applying such a fixator for fixation of tibia and other fractured long bones.

1. Introduction

Statistically, most human long bone fractures occur in the tibia [1]. Many types of internal and external fixators have been applied for fixation of this bone [2]. Locking compression plate (LCP) is one of the practical fixators that is widely used for this means. Orthopedists use LCPs with various numbers of holes to fix bone fractures [3]. Many types of LCPs have been manufactured. The recently manufactured LCPs have been designed with the combination holes which can house locking screws and the conventional ones [4]. Usually not all of the holes are used during operation and various arrangements of screws are used by the orthopedists. The optimum number and position of screws on plates have always been discussed among orthopedic surgeons [5,6]. Effect of stress shielding in the healing duration is one of the important problem caused by applying bone implants for a long time which can lead to

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porosity of bone, screw loosening and even failure of fixation [7].

Some studies previously have been carried out on finite element models of the human tibia [8–11]. In this study, a finite element based model of bone has been created based on computer tomography (CT) scan of the human tibia considering whole bone material including bone marrow and cancellous bone that have been mostly ignored in previous researches [12]. The model was mechanically validated and verified in comparison with the behavior of previous cadaveric bone studies [16]. Biomechanical effects of stress shielding, von Mises stresses in bone, plate and screws, also strain of gap or callus and stiffness using new defined parameters have been considered to obtain the preferred arrangement of six screws on 11 holes LCP in 5 terms of 16-weeks curing duration.

2. Materials and methods

2.1. *Modeling*

Bone modeling was done using CT scans for 375 mm length of the right tibia in a 32-year-old man with no skeleton problem. The scans were used in Mimics 10.01 for construction of the basic 3-D model. The resulting model was then exported to Solid works 2012 for some additional modeling requirements. The final model was imported in Abaqus 6.11-1 which was used for analysis. In the modeling procedure both cortical and trabecular parts of the bone were considered. Linear anisotropic elastic behavior of human long bone was defined to materialize the model. It had been known that the interior parts of tibia include medullary cavity, bone marrow and spongy bone but considering their low densities and so low influences on the results of mechanical loading, same as a previous study [13], these three parts were simplified and considered as a merged part which was named "low-density bone" in this study (Table 1). This was considered for the bone material when low amplitudes of loads were applied on the bone [14]. The element types were selected based on a previous research [15]. Meshing was done with 22,015 tetrahedral elements for low-density bone and 25,479 hexahedral elements for cortical bone (Fig. 1).

Fixation device was modeled based on the dimensions of a current commercial plate (Pars Co; #130504064602) with 11 combination holes and its locking screws. Meshing was done with 3249 and 480 hexahedral elements respectively for plate and screw (Fig. 1c).

Table 1 – Material properties of cortical and low-density bone [13].

Material properties	Cortical bone	Low-density bone
Young's modulus (MPa)	$E_x = 18.400$ (longitudinal) $E_y = 7.000$ (transverse) $E_z = 8.500$ (radial)	$E = 1.061$
Poisson's ratio	$\nu_{xy} = 0.12$ $\nu_{yz} = 0.37$ $\nu_{xz} = 0.14$	$\nu = 0.225$

The callus was modeled as a 1 mm thick section in exactly the middle of the bone model and was meshed with 888 hexahedral elements. Also two hollow cylinders were created with quadratic elements for loading to simulate the four points bending of the structure.

2.2. *Loading and validation of intact bone model*

At first, for studying this issue that the mechanical response of the model had no significant deference with the real human bone and its mechanical loading results could be verifiable, the modeled bone was loaded based on the way applied by Luca and Marco [16] and then the loading results were compared to those study results. So a 500 Nm torsional couple loading was applied in the proximal-distal direction and 500 N four points for both anterior–posterior and medial–lateral bending loads were applied on the model in ten increments. The resultant calculated stiffness's of the 3D model were compared with those taken from an average of 5 cadaveric bones (cadaveric bones codes #972, #973, #974, #975 and #976 of Luca and Marco [16] study which had close resemblance in length to the model used in current research).

2.3. *Loading of fixated fractured bone with various treatments just after surgical operation*

After the validation was complete, a 1 mm transverse extrusion was done in the middle of the bone model. Plate and screws were assembled on the fractured tibia model with various screw arrangements [17] (Table 2) and all of the

Table 2 – Various arrangements of screws on the 11 holes plate [17].

Treatment	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Control	L[a]	L	L	L	L	–	L	L	L	L	L
1	L	L		L		–		L		L	L
2	L		L		L	–	L		L		L
3			L	L	L	–	L	L	L		
4	L	L	L			–			L	L	L
5	L			L	L	–	L	L			L
6		L		L	L	–	L	L		L	
7	L	L			L	–	L			L	L
8		L	L	L		–		L	L	L	

[a] "L" shows a LCP hole which houses a locking screw.