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Research Paper

Biomechanical evaluation of intramedullary nail and bone plate for the fixation of distal metaphyseal fractures

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ABSTRACT

Surgical treatment of distal metaphyseal fractures remains problematic, and whilst both intramedullary nailing and bone plate fixation are known as the acceptable methods for the internal fixation of this kind of fractures, neither technique demonstrated satisfactory clinical outcomes. In this research, a finite element based investigation was made to compare these two fixation techniques for the fixation of distal tibia fractures from the biomechanics point of view. For this purpose, a 3 mm transverse fracture gap was created at the distal metaphyseal region of tibia and fixed by use of either a nail or a plate. The von Mises stress, interfragmentary movements, and the production of different tissue phenotypes at the fracture site were calculated. Results of this study showed that plating offers more advantageous biomechanical conditions at the fracture site, in which it provides sufficient amount of axial interfragmentary movement and considerable amount of cartilage production, while intramedullary nailing restricts axial movements but causes high magnitude of shear movements. However, nailing is superior to plating from the mechanical point of view and provides earlier weight bearing. In addition, it was shown that by using composite materials, biomechanical behavior of both fixation techniques will be improved through decreasing risk of failure and promoting cartilaginous tissue production.

1. Introduction

Distal metaphyseal fractures occur in about 10% of total tibial fractures (Bedi et al., 2006). Bone plates and intramedullary (IM) nail are two fixation methods that have been frequently used as stabilizers for distal tibial fracture (Casstevens et al., 2012). Clinical studies demonstrated that neither of these two fixation methods is preferable (Bedi et al., 2006; Behgoo et al., 2009; Guo et al., 2010; Janssen et al., 2007; Newman et al., 2011; Richard et al., 2014; Yu et al., 2015). Most studies reported considerably high rate of malunion for IM nail compared to the plate, but the later approach causes extensive dissection of soft tissue that leads to high rate of infection (Casstevens et al., 2012; Janssen et al., 2007;

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Newman et al., 2011; Richard et al., 2014; Vallier et al., 2011; Xue et al., 2014; Yu et al., 2015). However, there is no decisive report about superiority of one fixation method over another with regard to the union time (Xue et al., 2014; Polat et al., 2015).

Strauss et al. (2007) conducted experimental test on cadaveric specimens and reported high rigidity of bone–plate system compared to bone–nail. Another experimental study, done by Hoegel et al. (2012) on artificial tibia specimens, reported opposing results to Strauss et al. (2007). They evaluated fracture interfragmentary movement (IFM) for both fixation techniques and showed much higher IFM for the plate fixation, which states higher stiffness of the nailing in comparison with the plate fixation (Strauss et al., 2007).

There is evidence that mechanical conditions of fracture gap, determined by fixation stability, can be determinant for healing outcome (Claes et al., 1997; Goodship and Kenwright, 1985; Carter et al., 1988). Biological fixation refers to a fixation that brings enough flexibility to bone-implant construct to allow considerable production of cartilaginous tissue (Perren, 2002). Two advantages of biological fixation over rigid fixation are: first, by producing large amount of cartilage, the volume of callus increases, and thus the risk of implant hardware failure decreases by early weight bearing of callus; and secondly, the biological healing is able to tolerate deleterious effects of instability resulting from screw loosening which occurs because of the stress shielding phenomenon (Perren, 2002; Haase and Rouhi, 2013).

Axial interfragmentary strain defined as axial IFM over initial gap length was frequently used as an indicator of the healing efficiency (Hoegel et al., 2012; Kim et al., 2011; Claes et al., 1998; Duda et al., 1997). Axial IFM in the range of 7–33 is reported to cause secondary healing and normal callus production (Claes et al., 1997). Animal experiments and measurements on human patients have shown that IFM are not limited to axial direction, but in some cases shear movement is dominant (Duda et al., 2003; Augat et al., 2003; Klein et al., 2003). Limits of acceptable shear movement have not yet been defined, but it can be roughly concluded that, based on the investigation of the existing papers in the literature (such as Augat et al., 2003; Klein et al., 2003; Aro et al., 1991; Bishop et al., 2006; Epari et al., 2006; Park et al., 1988), the shear movement should not be much greater than the axial movement. Furthermore, there are some mechanobiological theories that make a correlation between mechanical stimuli and stem cells differentiation (Isik et al., 2012). The theory proposed by Prendergast et al. (1997) can predict tissue differentiation by using biophysical stimuli of the combined deviatoric strain and fluid phase velocity.

Despite considerable clinical studies (Bedi et al., 2006; Behgoo et al., 2009; Guo et al., 2010; Janssen et al., 2007; Newman et al., 2011; Richard et al., 2014; Yu et al., 2015), there is still a great controversy on the ideal surgical choice between IM nail and plate for the treatment of distal tibial fracture. Besides, the two in-vitro studies found in the literature (Strauss et al., 2007; Hoegel et al., 2012) not only could not help address this controversy, e.g. by proposing a mechanically stiffer construct, but also made the case even more problematic since provided contradictory results. This study was set to make a comparison between IM nailing and bone plating for the fixation of distal metaphyseal tibia fractures in order to understand advantages and disadvantages of either technique. Material properties of implants, screw positioning, and loading conditions were assumed as crucial parameters and probable causes of existing contradictions between similar studies, and their impacts on the performance of these two fixation devices were taken into consideration. In this study, the primary goal was to evaluate IM nailing and plating techniques from the mechanical point of view in order to address contradiction made by two in vitro studies (Strauss et al., 2007; Hoegel et al., 2012), and the main goal of this investigation was to determine the biological aspects of each method of fixation, i.e. the quality of bone healing process, which was not tackled by other investigators to date, to the best of our knowledge.

2. Materials and methods

In this section, details of the finite element modeling of tibia-implant assembly were presented. The first three subsections are focused on the process of geometry development, i.e. geometry of tibia, nail, plate, screw, and how they were assembled to create a tibia-implant construct. Then, in the subsequent subsections, explanations can be found about modeling material properties, boundary conditions, and finally, analysis procedure and calculation were determined.

2.1. *Construction of the bone CAD model*

To create a CAD model, CT data of a 65 years old male's right tibia and his right femur distal condyle were used by considering cross- sectional images at every 1 mm slice along the longitudinal axis of the tibia-femur. The point clouds obtained by Mimics (V.10.01) were imported to Catia (V5.R19) for making the solid structure. A 3 mm transverse gap was simulated in the distal area of tibia, which is located 5 cm away from articular surface of tibio-calcaneal joint (AO classification: 43-A3).

CAD models of an intramedullary nail (Expert, diameter: 9 mm, length: 330 mm, Synthes) and bone plate (LCP Distal Tibia Plates, 6-Hole, Synthes) were constructed and assembled to tibia. By means of an orthopaedic surgeon, IM nail was inserted into medullary canal (Fig. 1a) in which the distance of the end of nail from the articular surface was about 1 cm (according to suggestion of AO Surgery Reference), and plate was positioned in the medial side of tibia (Fig. 1b). In order to simulate reaming process, medullary canal diameter was assumed to be 1 mm wider than nail diameter (Duda et al., 2001). As shown in Fig. 1a, excessive closeness of the fracture site to the articular surface causes screw hole ❸ to be placed in the middle of the fracture gap, hence to improve application of nail, as well as to prevent stress concentration around this hole, position of the hole was modified and moved 2 cm above the fracture gap. For the sake of simplicity, the threads of the implant holes and screws were all neglected, and screws were modeled as a cylinder with a truncated cone head. External callus was modeled with a callus index of 1.4 (Byrne et al., 2011; Lacroix and Prendergast, 2002), as shown in Fig. 1c.