The biomechanical effect of bone quality and fracture topography on locking plate fixation in periprosthetic femoral fractures

Andreas Leonidou a,*, Mehran Moazen b, Panagiotis Lepetsos a, c, Simon M. Graham a, George A. Macheras c, Eleftherios Tsiridis a, d

a Academic Department of Orthopaedics and Trauma, Division of Surgery, Aristotle University Medical School, University Campus, 54 124 Thessaloniki, Greece
b Medical and Biological Engineering, School of Engineering, University of Hull, Hull HU6 7RX, UK
c 4th Department of Trauma & Orthopaedics, KAT Hospital, Nikis 2, Kifissia, 14561 Athens, Greece
d Department of Surgery and Cancer, Division of Surgery, Imperial College London, B-block Hammersmith Hospital, Du-Cane Road, London W12 0HS, UK

ARTICLE INFO

Article history:
Accepted 22 October 2014

Keywords:
Periprosthetic femoral fracture
Bone quality
Fracture angle
Fracture level
Fracture topography
Finite element analysis

ABSTRACT

Optimal management of periprosthetic femoral fractures (PFFs) around a well fixed prosthesis (Vancouver B1) remains controversial as adequate fixation needs to be achieved without compromising the stability of the prosthesis. The aim of this study was to highlight the effect of bone quality i.e. canal thickness ratio (CTR), and fracture topography i.e. fracture angle and its position in relation to the stem, on the biomechanics of a locking plate for a Vancouver B1 fracture. A previously corroborated simplified finite element model of a femur with a cemented total hip replacement stem was used in this study. Canal thickness ratio (CTR) and fracture topography were altered in several models and the effect of these variations on the von Mises stress on the locking plate as well as the fracture displacement was studied. Increasing the CTR led to reduction of the von Mises stress on the locking plate as well as the fracture movement. In respect to the fracture angle with the medial cortex, it was shown that acute angles resulted in lower von Mises stress on the plate as opposed to obtuse angles. Furthermore, acute fracture angles resulted in lower fracture displacement compared to the other fractures considered here. Fractures around the tip of the stem had the same biomechanical effect on the locking plate. However, fractures more distal to the stem led to subsequent increase of stress, strain, and fracture displacement. Results highlight that in good bone quality and acute fracture angles, single locking plate fixation is perhaps an appropriate management method. On the contrary, for poor bone quality and obtuse fracture angles alternative management methods might be required as the fixation might be under higher risk of failure. Clinical studies for the management of PFFs are required to further support our findings.

© 2014 Elsevier Ltd. All rights reserved.

Introduction

Total hip arthroplasty (THA) is complicated by periprosthetic femoral fractures (PFFs), with incidence varying from about 1% for cemented and 5.4% for uncemented primary prostheses [1,2]. The majority of the PFFs are located around the tip of the stem and are subdivided as B1 with the stem stable, B2 with the stem unstable and B3, with significant bone loss, according to the Vancouver classification [3]. Optimal management of Vancouver B1 periprosthetic femoral fractures around a well fixed prosthesis remains controversial as adequate fixation needs to be achieved without compromising the stability of the prosthesis [2].

Locking plates have been frequently used in the management of B1 PFFs with variable published results [2,4,5]. Over recent years there has been an increase in number of PFF fixation failure reports including locking plates [2,4,5]. While various studies are investigating development of new fixation methods for these fractures, patient bone quality, stem stability and fracture level are also considered as contributing factors to the success or failure of PFF fixations [1,2].

A recent clinical study by Leonidou et al. highlighted that fracture angle may also need to be considered as an independent parameter when contemplating a treatment method for Vancouver type B1 fractures [1]. Regardless, the definition of bone quality and fracture level in B1 fractures is also not clear [1].

Therefore the underlying hypothesis of this study was that, bone quality, fracture angle and level (fracture topography) can change the biomechanics of PFF fixation in B1 fractures where...
some cases might be at higher risk of failure. The specific aim of this study was to illustrate the effect of bone quality, fracture angle and level in a simplified finite element (FE) model replicating a Vancouver B1 fracture. It must be mentioned that the simplified model has been widely used in literature to understand the biomechanics of fracture fixation and was validated against a clinical case study in one of our recent studies [6]. Nevertheless, due to its simplified nature our results here have intended as a preliminary investigation where the emphasis has been put on the pattern of FE results rather than their exact predictions.

Materials and methods

Model description

A simplified parametric finite element model of a cemented total hip replacement (Fig. 1) was developed previously by Moazen et al., and was adopted in this study [7]. The model was validated against a clinical case study [6]. The bone, stem and the cement were modelled as concentric cylinders. A transverse fracture below the tip of the stem was created and fixed laterally with a ten holes plate. In order to achieve an appropriate bridging length, two holes in the centre of the plate (i.e. across the fracture line) were left empty [8]. The fracture was held in place with four unicortical screws proximally and four bicortical screws distally [9,10]. The screws were modelled as cylinders with a diameter of 4.5 mm corresponding to common diameter of locking cortical screws used in the femur [11]. The plate was placed directly on bone, as it has been shown that direct contact of the locking plate with the bone in combination with two holes of working length resulted in decreased stresses on the construct [8]. All parts of the model were assigned isotropic materials properties with a Young modulus of 2 GPa for cement, 20 GPa for bone and 200 GPa for the metal plate and screws [12]. A Poisson's ratio of 0.3 was used for all materials.

Boundary conditions and loads

The stem–cement, cement–bone, and screw head–plate interfaces were tied together. Interaction at the plate–bone interface was modelled with contact elements with coefficient of friction of 0.3 [13]. Interfaces at the fracture site were also modelled with contact elements with coefficient of friction of 0.04, corresponding to early stages of fracture healing, where no callus has formed between the two fragments [7]. The distal part of the model was rigidly fixed and the proximal part of the stem was loaded with a transverse force equal to \( P = 5W \times \sin\theta \), where \( W \) was the body weight and \( \theta \) was the loading angle between the line of action of gravity and the long axis of femur. Body weight of 600 N and loading angle of 11° were used in this study [12].

Mesh sensitivity

The model was meshed with Tetrahedral (C3D4) elements. Convergence was tested by increasing the number of elements from 42,000 to 1,600,000 in five steps. The solution converged on the parameters of the interest (<5% for von Mises stress across the two empty screw holes where the plate is at high risk of failure [7,12,13]) with approximately 300,000 elements. Models with this number of elements or more were used for each of the cases presented.

Bone quality and fracture topography

Three models with different canal thickness ratio (CTR) were developed representing poor, average and best bone quality with respective CTROS of 0.44, 0.88 and 1.46 (Fig. 2). This was done based on our previous study, which indicated that bone quality can vary within Vancouver B1 fractures [1]. Further three models were developed with angle fractures varying from the unstable transverse (0°) and short oblique (146°) to the stable long oblique configuration (76°) (Fig. 3). Finally, three models were developed with the fracture at the tip of the stem, 4 mm and 14 mm below the tip of the stem (Fig. 4).

Simulations and measurements

The models were solved and analysed using a finite element simulation package (ABAQUS v. 6.9, Simulia Inc., Providence, RI, USA). The pattern of von Mises stress on the plate and fracture movement was compared across the cases. Fracture movement was quantified as the relative displacement of the most distal point of the proximal fragment and the most proximal point of the distal fragment on the medial side of the bone.

Fig. 1. Simplified model as created in Abaqus CAE Software.

Fig. 2. Sagittal view of the model showing different bone quality configurations: (A) worst bone quality (CTR = 0.44); (B) average bone quality (CTR = 0.88); (C) best bone quality (CTR = 1.46).
Fig. 3. Finite element models and the relevant angles of the PFF. A is a transverse fracture, B equals to 76° and C is a fracture with a 146° angle.

Fig. 4. Finite element models and the relevant level of the PFF. (A) Fracture at the tip of the stem, (B) 4 mm below the tip and (C) 14 mm below the tip.

Results

Increasing the bone quality (CTR) led to reduction of von Mises stresses on the locking plate. The fracture displacement was also decreased. In respect to the fracture angle with the medial cortex, it was shown that acute angles resulted in lower level of von Mises stress on the plate as opposed to obtuse angles. Furthermore, acute fracture angles resulted in lower fracture movement. Fractures around the tip of the stem (0 and 4 mm) had the same biomechanical effect on the locking plate. However, as the distance of the fracture from the tip was increased at 13 mm the von Mises stresses and fracture movement were also increased. Numerical results of the FE are summarized in Table 1. Pattern of von Mises stress around the empty screw holes of the plate for all the models is shown in Figs. 5–7.

Discussion

The results of this study confirm our hypothesis that poor bone quality, unstable patterns of fractures, and fractures below the tip of the stem in Vancouver B1 fractures increase the mechanical stress on the locking plate as well as fracture movement under loading.

Finite element analysis results from this study highlighted that the worse bone quality model exhibited increased levels of stress around the empty screw holes (i.e. potentially leading to fixation failure [7,8,14]), as well as increased fracture displacement (i.e. potentially leading to non-union). Considering that Vancouver classification does not take into account the variation that exists in the bone quality in B1 fractures, the preliminary results of this study suggest that perhaps B1 fractures with low CTR need to be treated with cautions. Nevertheless, what classifies as a low CTR based on a plan X-ray requires further investigation [1].

The fracture angle was shown to have a considerable effect over the distribution of the von Mises stress on the locking plate. The worse results were recorded with the short oblique (146°) model and the best ones with the long oblique (76°) model with the transverse fracture results being within the range of long and short oblique fractures. These results confirm the inherent instability of the transverse and short oblique PFF and question the suitability of single locking plate alone for the management of these injuries. The orthopaedic surgeon might therefore consider that short oblique and transverse fractures are unstable and require stronger and more secure fixation in all planes [15,16].

The level of the PFF is an important parameter of its personality. In this study it was shown that von Mises stresses and fracture movement were increased as the fracture occurred more distal to the tip of the stem (Table 1). More specifically, for a fracture 14 mm

<table>
<thead>
<tr>
<th>Bone quality</th>
<th>von Mises (MPa)</th>
<th>Fracture displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1 (worst)</td>
<td>168</td>
<td>0.53</td>
</tr>
<tr>
<td>Model 2 (average)</td>
<td>111</td>
<td>0.37</td>
</tr>
<tr>
<td>Model 3 (best)</td>
<td>104</td>
<td>0.27</td>
</tr>
<tr>
<td>Fracture angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1 (0°)</td>
<td>111</td>
<td>0.37</td>
</tr>
<tr>
<td>Model 2 (76°)</td>
<td>60</td>
<td>0.10</td>
</tr>
<tr>
<td>Model 3 (146°)</td>
<td>342</td>
<td>0.72</td>
</tr>
<tr>
<td>Fracture level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1 (tip)</td>
<td>114</td>
<td>0.30</td>
</tr>
<tr>
<td>Model 2 (4 mm below)</td>
<td>111</td>
<td>0.37</td>
</tr>
<tr>
<td>Model 3 (14 mm below)</td>
<td>139</td>
<td>0.75</td>
</tr>
</tbody>
</table>
away from the tip of the stem the fracture displacement was twice higher as opposed to a fracture at the tip of the stem. This highlight the importance of identifying a clear border between Vancouver B and C type fractures. Regardless, our results suggest that single locking plate in distal femoral fractures can be under high level of stress [5]. The importance of fracture level was identified by Bryant et al., as they claimed that the B1 fractures around the tip of the stem are the most challenging to treat [17]. They further advocated the use of long locking plates spanning the whole femur with multiple screws for the management of this type of fracture [17]. Choi et al. further suggested that single locking plate fixation may not be adequate for comminuted B1 PFF occurring at or near the tip of the stem [18]. They suggested supplementation of the locking plate fixation either with an allograft or with an anterior plate [18]. Results obtained in this study further suggest that distal fractures can increase the stress level on the single locking plate fixation. This could potentially explain reported cases of locking plate failure and pullout when used for the management of distal PFF [5,19].

Fracture displacement was studied in the FE models and is of paramount importance as it disturbs the continuity of the medial cortex of the femur and can potentially affect the healing process. The importance of the medial cortex was outlined by Corten et al., as they suggested that a lateral plate alone was suitable for the fixation of a B1 PFF only if the medial cortex was anatomically reduced and not comminuted [20]. They further advised biplanar fixation if the medial cortex was disrupted, as they thought that this fracture configuration would be more unstable [20]. Furthermore, fracture displacement and movement are known risk factors for delayed healing, which can subsequently interpret the documented delayed and non-unions of B1 PFF treated with locking plates [4,11,21].

This study is to the best of authors’ knowledge the first one to investigate the effect of fracture topography and bone quality on locking plate fixation for a Vancouver B1 PFF. One of the key advantages of the simplified model used in this study was that the effect of different parameters on the stress level of the fixation could be isolated. At the same time, one of the main limitations of this FE model is that it has not been corroborated with a biomechanical experimental model yet was validated against a clinical case study [6]. Nevertheless, similar simplified femoral models have been extensively used in the literature and have been validated both on theoretical and on biomechanical grounds [8,22,23]. More specifically, both Iesaka et al. and Stoffel et al. corroborated their simplified femoral model against experimental model [8,23]. Furthermore, published data from biomechanical and clinical studies – with different experimental setup – revealed increased stresses and subsequent failure through the empty holes of the locking plate, which agree with the findings of the current study [4,8,24,25]. Therefore, despite the limitations of the
validation process, relative comparisons that were made in this study between the models remain valid.

This study suggests that the orthopaedic surgeon should contemplate on the PPF topography and bone quality and not rely merely on the Vancouver Classification in order to formulate a treatment plan. More specifically, in Vancouver B1 fractures with unstable patterns, away from the tip of the stem with poor underlying bone stock, the surgeon might consider alternative methods to enhance the single locking plate fixation. This can include increasing the plate length, revision to long stem or applying bone allograft. Further clinical, biomechanical and computational studies need to be conducted focusing on the fracture personality and not only on the locking plate configuration.

Conflict of interest

None declared.

References