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Working length of locking plates determines interfragmentary movement in distal femur fractures under physiological loading

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ABSTRACT

Background: This study aimed to investigate the influence of the screw location and plate working length of a locking plate construct at the distal femur on interfragmentary movement under physiological loading.

Methods: To quantitatively analyse the influence of plate working length on interfragmentary movements in a locking plate construct bridging a distal femur fracture, a finite element model based on CT (computed tomography) data was physiologically loaded and fracture gap conditions were calculated. Four working lengths with eight screw variations each were systemically analysed.

Findings: Interfragmentary movements for axial (12–19%, $p < 0.001$) and shear movements (−7.4–545%, $p < 0.001$) at all tested nodes increased significantly with longer plate working length, whereas screw variations within the groups revealed no significant influence. The working length (defined by screw location) dominates the biomechanical fracture gap conditions.

Interpretation: The current finite element analysis demonstrates that plate working length significantly influences interfragmentary movements, thereby affecting the biomechanical consequences of fracture healing.

1. Introduction

Fractures of the distal femur are rare but serious injuries, with an estimated incidence of 0.4% of all fractures and 3% of femur fractures (Court-Brown and Caesar, 2006). A bimodal distribution is found with young patients (approximately 30 years of age) predominantly suffering from high velocity accidents and with elderly patients mainly experiencing low energy trauma (Ehlinger et al., 2013). Stable fixation of these fractures to resist forces and strains on the femur under physiological loading can only be realised with osteosynthetic reconstruction either by plating or nailing (Ehlinger et al., 2013). Prior to the introduction of locking plates with angular stable screw anchorage, open reduction and internal fixation using conventional plates was the gold standard (Claes, 2011; Dobele et al., 2014). The need for wide surgical approaches led to devascularisation of the fragments resulting in high complication rates and disturbances of fracture healing (Augat et al., 2005). In recent years, the internal fixation philosophy of long bone fractures with extramedullary implants has changed from mechanical to biological priorities (Perren, 2002). The focus has been on percutaneous techniques (MIPO) requiring "no touch" of the fracture zone that resulted in minimal surgical trauma and preserved the fracture vascularity (Perren, 2002). These so-called "biological osteosyntheses" caused changes in the biomechanical principles of fracture fixation and biomechanical processes of fracture healing (Claes, 2011; Dobele et al., 2014). Whereas compression plates aim for direct fracture healing, bridging plates aim for secondary healing via callus formation, which is induced by the elastic fixation (Claes, 2011; Duda et al., 2003; Perren, 2002). Many authors, including our group, could demonstrate that an axial compression distance of 20–30% of the gap length in a 3 mm fracture gap leads to complete fracture healing within 9 weeks in a sheep model, while higher axial or combined axial and shear interfragmentary movements (IFMs) delay healing significantly (Goodship and Kenwright, 1985; Schell et al., 2005; Wolf et al., 1998). The IFM can be partly controlled by the stiffness of a fixation construct. In internal fixation, the number and location of screws within the construct determines the stiffness as opposed to in external fixation where the number of pins as well as the distance between the fixator elements and the bone axis are the main factors (Stoffel et al., 2003). Axial stiffness and torsional rigidity are mainly influenced by the working length of the plate construct (distance between the first screw at each side of the fracture) (Stoffel et al., 2003). To date, the implant length, number and location of screws along the plate is more dependent on the surgeon's experience than on biomechanical evidence. Current recommendations suggest that bridging plates should be as long as suitable and that at least three bicortical screws at each side of the fracture are necessary (Hoffmann et al., 2013; Stoffel et al., 2003). While the stiffness of fracture fixation is generally evaluated

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in vitro under simplified loading conditions, it remains unclear how it is influenced by different screw positions under physiological loading (Claes et al., 1999; Stoffel et al., 2003). So far, the relationship between the working length of a locking plate system and IFM remains unknown.

This study aimed to systematically investigate the influence of both the screw location and plate working length of an anatomically pre-shaped locking plate construct at the distal femur on the IFM under physiologic loading. Based on these findings, recommendations for clinical practice may be formulated.

2. Methods

To quantitatively analyse the influence of plate working length on IFM in a locking plate construct of a distal femur fracture, a finite element (FE) model was developed.

2.1. Geometry

We chose a data set with gait cycle data, quantitative computed tomography (qCT) and ground reaction force data of a representative patient from a previously published study that was comparable to the data published elsewhere (Boyer et al., 2012; Szwedowski et al., 2012). Using the qCT data, a specific FE model was extracted using Amira v5.3 (Visage Imaging, San Diego, USA) for segmentation and smoothing, Geomagic Studio 10 (Geomagic, Morrisville, USA) for reprocessing and creation of Non-Uniform-Rational-B-Spline (NURBS) and Abaqus/CAE v.6.9 (Dassault Systèmes, Vélizy-Villacoublay, France) for discretisation as a solid body. The model was meshed with second-order tetrahedral elements (C3D10) with strong refinement in areas of high local curvature. The initial mesh seed was set to 7 mm (resulting characteristic element length 1.67 mm, 240,798 DOFs). This mesh was verified to be suited to yield consistent results in reaction forces, surface strain and displacement with finer meshes (Fig. 1a).

2.2. Material model

A significant correlation between the qCT image density (HU) and the mineral density of a known phantom could be shown ($R^2 > 0.999$; $p < 0.001$) and formed the base for a linear regression formula to calculate the mineral density. A nonhomogeneous material distribution (material mapping approach) was modelled based on averaged image densities over each mesh element and mineral densities were calculated. These acquired equivalent densities were calibrated according to Schileo et al. and an apparent density-isotropic stiffness relation was used as described by Morgan et al. (2003) and Schileo et al. (2008). This proceeding gives a material property estimate to allow an assumption of physiological conditions and has been shown to result in numerical calculations that are in accordance with experimental measurements (Schileo et al., 2007). Finally, the materials were grouped into bins (size 50 MPa) according to a range of stiffness resulting in more than 400 material definitions.

2.3. Simulation of a comminuted fracture and osteosynthetic stabilisation

A comminuted fracture without cortical support was modelled at the distal femur. The fracture was simulated by creating a 10 mm osteotomy gap (this distance has been shown to avoid cortical contact while loading (Chao et al., 2013)) between the distal and proximal fragments by removing elements 68 mm above the lateral condyle (location of the first plate hole at the shaft, Fig. 1). In order to mimic conditions representing 80 days postoperatively (when patients are able to walk with full weight bearing) four diagonally spanning spring elements

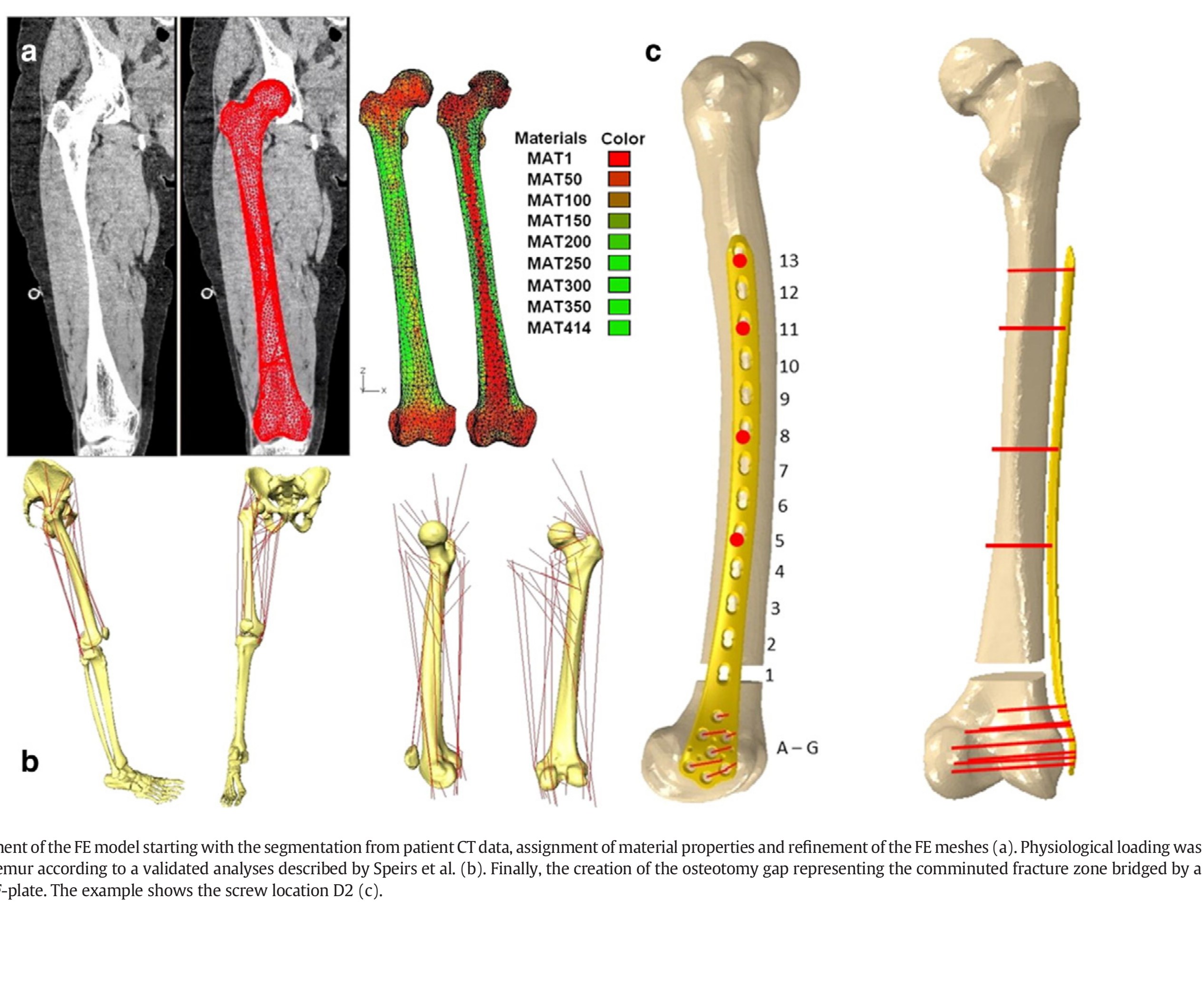

Fig. 1. Development of the FE model starting with the segmentation from patient CT data, assignment of material properties and refinement of the FE meshes (a). Physiological loading was applied to the femur according to a validated analyses described by Speirs et al. (b). Finally, the creation of the osteotomy gap representing the comminuted fracture zone bridged by a 13-hole-LISS-DF-plate. The example shows the screw location D2 (c).