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Finite element modelling of a unilateral fixator for bone reconstruction: Importance of contact settings

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ABSTRACT

When reconstructing a large segmental bone defect by means of a porous scaffold, a fixator is used to stabilize the reconstruction. The fixator stiffness is an important factor as it will influence the biomechanical environment to which scaffold and regenerating tissues are exposed. A finite element (FE) model can be used to predict the fixator stiffness. The goal of this study was to develop and validate a detailed 3D FE model of a custom-developed unilateral external fixator. In particular, it was hypothesized that the contact interfaces between the different fixator components play a major role for the prediction of the fixator stiffness. *In vitro* mechanical testing of the entire fixator as well as of separate fixator components was performed in order to measure the stiffness. The mechanical test set-ups were simulated by means of detailed FE models that considered different levels of refinement of the various contact interfaces. The error on predicted fixator stiffness in comparison to measured stiffness was reduced from 121% to 16% by refining the contact settings of the FE model. The individual sources of error between the measured and predicted fixator stiffness could be quantitatively assessed as well. In conclusion, this study warrants for a careful modelling of the geometry and contact settings, when using FE models for the prediction of fixator stiffness.

1. Introduction

The repair of large bone defects, e.g. due to trauma, infection or bone tumours, remains a major clinical problem. Tissue engineering may present an alternative to more traditional treatments, such as distraction osteogenesis. By using an appropriate combination of a (porous) carrier, (osteogenic) cells and biochemical signals, bone formation in and around the carrier may be stimulated [1,2]. In the case of bone reconstruction of large segmental defects in load-bearing bones, either internal or external fixation will be used to stabilize the reconstructed bone [3]. In order to avoid mechanical failure of the construct, it is important to choose an appropriate fixator stiffness. In addition, as bone regeneration (such as during fracture healing) is known to be influenced by mechanical loading [4–8] the *in vivo* mechanical environment to which the cells inside and around the construct are exposed, may influence the biological response [9,10]. A quantification of this environment is therefore needed in order to better understand its influence. Again, the fixator stiffness will be an important factor and has to be determined accurately, which may involve mechanical testing and mathematical modelling. Many studies have reported the use of analytical models to predict global fixator stiffness and interfragmentary movement [11–15]. During fixator design, more detailed three-dimensional solid finite element (FE) models can be used to provide additional information on stresses in fixator components (e.g. to asses fracture risk) and the effect of fixator component design on fixator stiffness [16,17].

The goal of this study was to develop and validate a detailed 3D FE model of a custom-developed unilateral external fixator. In particular, we hypothesized that the contact between the different fixator components plays a major role for the prediction of the fixator stiffness. The study is relevant for the design of (external) fixators for bone reconstruction and for an accurate prediction of fixator stiffness, when using detailed FE models.

2. Materials and methods

2.1. Mechanical testing

An idealized segmental defect, representative for a previously developed long bone defect model in rabbits [18], was reproduced experimentally by using a hollow polyoxymethylene (POM; VINK

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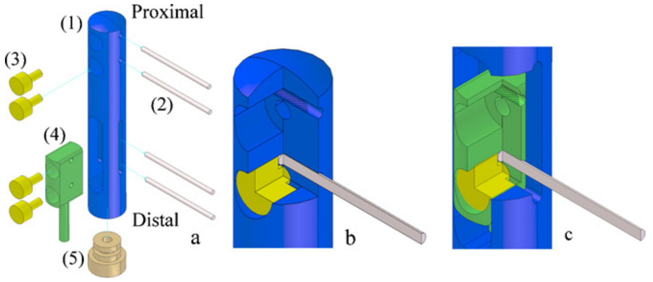

Fig. 1. (a) Exploded view of fixator: fixator body (1), fixator screws (2), bolts (3), sliding part (4) and axial positioning screw (5). The sliding part enables to adjust the distance between proximal and distal screws. During function '4' and '5' are locked, preventing any axial movement. (b) Section view of proximal and (c) distal part of fixator. In the empty drill hole, crosshatching shows the contact area that experiences the compressive preload due to bolt tightening.

NV, Belgium) tube of 10 mm outer diameter, 4 mm inner diameter and 120 mm length. A custom-made unilateral fixator (Fig. 1a) consisted of four 2 mm screws (Apex Self-drilling Half Pin screw, diameter 2 mm; Stryker NV, Belgium) and a fixator body made from stainless steel. Each screw was inserted into a drill hole (clearance of 0.1 mm) in the fixator body and clamped by tightening a bolt (M 4), which resulted in a compressive force between the screw and the bolt end (Fig. 1b and c; see crosshatched area). The fixator was mounted on the tube by means of two proximal and distal screws and a 20 mm segmental defect was created. The distance between the tube and the fixator body (free screw length) was set to 10 mm (Fig. 2).

The specimens (further denoted 'entire fixator') were tested in a universal material testing machine (Instron 4467, Instron Corporation, Norwood, USA). In order to keep the specimen in place, a 20 N preload was applied to the proximal POM end followed by a vertical displacement. The reaction force up to 100 N (including preload) and the interfragmentary (axial) displacement were measured by means of a load cell (Instron 2525–806; 1 kN range) and an extensometer (Instron 2620–601; 5 mm travel) respectively and plotted with respect to each other in order to calculate the specimen axial stiffness as the slope of the force–displacement curve [3,11,15]. The tests on the entire fixator were performed on 3 POM specimens.

In order to assess the importance of the different contact regions for the overall stiffness (and the correct FE modelling thereof, see below), the stiffness of following specimen parts was measured separately: (i) fixation of screw to POM tube (further denoted 'SCREW-POM'), (ii) fixation of proximal screw to fixator body ('SCREW-PROXIMAL') and (iii) fixation of distal screw to fixator body ('SCREW-DISTAL'). For each part, a vertical displacement was applied to the free screw end and the reaction force was measured (Fig. 4). The stiffness was always defined as the slope of the force-displacement curve. The cantilever length was 15 mm for SCREW-POM specimens and 12 mm for SCREW-PROXIMAL and SCREW-DISTAL specimen. A 1 N preload was applied so that all specimens were consistently set up. The reaction forces were limited to 20 N for SCREW-POM and 50 N for SCREW-PROXIMAL and SCREW-DISTAL in order to avoid permanent deformation of the different parts.

Additional stiffness measurements were performed on SCREW-PROXIMAL for a different contact condition between bolt, fixator body and screw. In particular, the bolt was not tightened, leading to a free contact between screw, bolt and fixator body. Although clearly not representative for the *in vivo* situation, it enabled to further analyze potential sources of error between the measurements and simulations (see further).

For all test conditions, stiffness measurements were repeated 6 times (6 loading-unloading cycles without unmounting the specimen from the testing machine) by applying a displacement rate at 0.5 mm/min, and a mean stiffness value was calculated. The Young's modulus of POM was measured by means of impulse excitation (GrindoSonic®, J.W. Lemmens N.V., Belgium) to confirm the manufacturer's data.

2.2. FE model

A 3D FE model, consisting of quadratic tetrahedral elements, was created for the experimental set-up (Fig. 2b). A convergence study was performed in order to establish the appropriate mesh refinement. The total number of elements and nodes was equal to 122,856 and 203,922, respectively. Simulations were run for the entire fixator as well as for the separate parts. All boundary conditions were set according to experimental test conditions. For the entire fixator, displacements at the distal end of the POM tube were fully constrained and a distributed axial force of 100 N was applied at the proximal end of the POM tube (Fig. 3). Boundary conditions for the separate parts are shown in Fig. 4. The load was applied incrementally by means of 10 equal time steps. The steel screws were assigned a Young's modulus of 190 GPa and a Poisson's ratio of 0.3 (manufacturer's data). These values were also applied to the fixator parts. POM was assigned a Young's modulus of 3 GPa, which

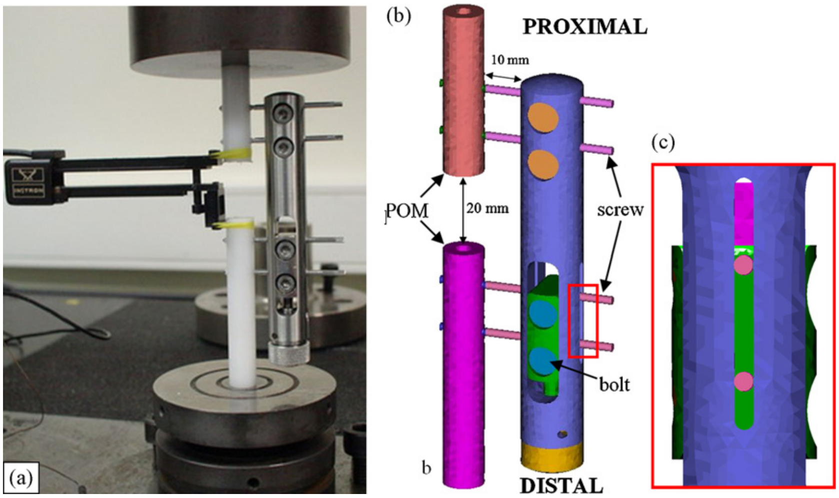

Fig. 2. (a) Mechanical test set-up of the entire fixator; the interfragmentary displacement was measured by means of an extensometer. (b) Geometrical model used for FE mesh creation. (c) Side view of distal fixator part (close-up view), showing the lateral slot.