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► **To cite this version:**

Sohrab Rezaei, Massamaesso Bilasse, Yamen Othmani, Samuel Berthe, Nadia Bahlouli, et al.. Numerical study of hinge fracture in distal femoral osteotomy using XFEM. 2024. hal-04738039

HAL Id: hal-04738039

<https://hal.science/hal-04738039v1>

Preprint submitted on 15 Oct 2024

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Numerical study of hinge fracture in distal femoral osteotomy using XFEM

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Keywords: Biomechanical study; bone fracture; distal femoral osteotomy; XFEM; crack propagation.

1. Introduction

Distal femoral osteotomy (DFO) is a surgical intervention primarily indicated for the correction of valgus malalignment of the knee, which is often associated with lateral compartment osteoarthritis. DFO procedure is performed by making a cut in the lateral side of the femur which creates a medial bony hinge allowing the surgeon to apply the correction. Hinge fractures during the opening can significantly affect postoperative outcomes and stability of DFO surgeries (Ogawa et al., 2017). Inserting a temporary protection K-wire passing through the hinge (Figure 1a) has been shown to reduce hinge fracture risk in the tibial osteotomy. Recently, Mereb et al. conducted a study to investigate the benefit of these K-wires for DFO (Mereb et al., 2023). Using ABS 3D-printed femurs, they experimentally showed that adding these K-wires would decrease the risk of medial hinge fracture.

From a mechanical point of view, the fracture of the hinge could be regarded as initiation and propagation of crack. Crack modelling using extended finite element method (XFEM) has shown to be plausible in modeling the fracture in bone. Marco et al. used this method to investigate the fracture in femoral head and managed to obtain a fracture pattern close to their experimental tests (Marco et al., 2018). There is no numerical study yet in the literature that applies XFEM to fracture in DFO.

The aim of this study is to numerically investigate the influence of adding a K-wire in the bony hinge on the fracture during opening phase of DFO, using XFEM.

2. Methods

We developed a finite element (FE) model to better understand the effect of K-wire on the risk of crack initiation and propagation. To validate this initial model, an experimental study on 3D-printed ABS bones by Mereb et al. was used. The model consists of a cortical outer layer with a thickness based on CT-scan and a trabecular structure filled inside the epiphysis. Two models were prepared to simulate cases without (KW-) and with k-wire (KW+). The analysis was performed under Abaqus FE software (Dassault Systèmes Simulia CorpTM). The geometry was meshed using linear tetrahedral elements (C3D4) with a size ranging from 0.3 to 1mm (obtained by convergence study) in the hinge area and grew bigger as it got further.

The material properties of both components were modeled as isotropic material with linear elasticity. The material properties of cortical part were obtained from the existing experimental data (Berthe, 2023). Elastic modulus was set to 2000 MPa and the critical energy release rate (G_I) to 5.8 KJ/m² for mode-I rupture. For mode-II and mode-III ruptures, the following equation was used based on the literature (Marco et al., 2018):

$$\frac{G_{II}}{G_I} = \frac{G_{III}}{G_I} = 0.33 \quad (1)$$

For trabecular component, the material properties were calculated using Voigt's method (Luo, 2022) for composites based on 30% volume fraction. Consequently, elastic modulus and critical energy release rate were defined as 600 MPa and 1.8 KJ/m², respectively. The K-wire was considered as a perfectly elastic-plastic steel material, with elastic modulus of 210 GPa and yield stress of 300 MPa.

Fracture was modelled using XFEM and maximum principal stress as crack initiation criterion with virtual closing crack technique (VCCT) for the propagation of the crack.

The distal part of femur was fixed by clamping the outer surface of over 15 mm from the osteotomy cut. Then, an opening force was applied by a cylindrical punch moving parallel to the cut (Figure 1a). The interface between punch and femur was defined by surface-to-surface contact using penalty formulation with a coefficient of friction of 0.05. The same contact method and properties as the punch were considered for the interface between K-wire and bony components.

3. Results and discussion

After implementing the simulations, Force-displacement curves for the punch head are obtained and they are given in Figure 1c for both cases. Overall, these graphs show a linear portion which indicates the elastic deformation of the assembly before that

propagation of the crack. Afterwards, the force drops occasionally but with an overall increase in its value showing a stable crack growth. Finally, a sudden drop is observed that is resulted by a rapid growth of the crack.

Comparing the two graphs shows that: firstly, the maximum force (hinge strength) is increased 42% by adding the K-wire. Secondly, the displacement in which the maximum force occurs is also 10% higher in KW+. This shows that adding a K-wire decreases the risk of fracture during the opening phase of DFO. This is in accordance with the results reported by Mereb et al.

Additionally, by following the crack surface evolution during the opening (Figure 1b), it can be noted that the overall surface area of the crack is smaller for KW+ and it is distributed more uniformly compared to KW- where the propagation is more concentrated on the anterior side of cut.

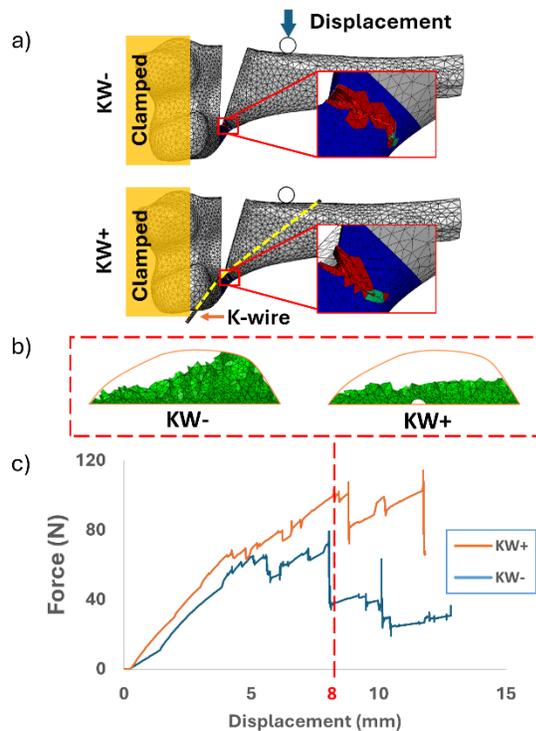


Figure 1. a) representation of the FE models without (KW-) and with the K-wire (KW+), b) evolution of the crack surface at 8mm displacement of the punch, c) force-displacement curves of punch

4. Conclusions

In this study, crack propagation and fracture during the opening phase of DFO was modeled using XFEM. Results showed that using a K-wire passing through the bony hinge increases the strength and limits the crack propagation of the hinge.

Although the overall behavior was in accordance with the experimental work of Mereb et al., the values show

a significant discrepancy. This could be because of the lack of data regarding the mechanical properties. Consequently, mechanical tests including uniaxial tension and compact tension toughness tests are planned for ABS material used.

Funding

This work of the Interdisciplinary Thematic Institute HealthTech, as part of the ITI 2021-2028 program of the University of Strasbourg, CNRS and Inserm, was supported by IdEx Unistra (ANR10-IDEX-0002) and SFRI (STRAT'US project, ANR-20-SFRI-0012) under the framework of the French Investments for the Future Program.

Conflict of Interest Statement

The authors declare no potential conflicts of interest with respect to this research.

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Received date: 07/04/2024

Accepted date: 28/06/2024

Published date: XX/XX/2024

Volume: 1

Publication year: 2024