Original article

Effect of saw blade geometry on crack initiation and propagation on the lateral cortical hinge for HTO: Finite element analysis

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A B S T R A C T

Introduction: The hinge plays a primary role in the hold and healing of a high tibial osteotomy (HTO). Weakening of the hinge is a risk factor for failure. The aim of our study was to determine whether the geometry of the saw blade's cutting edge impacts crack initiation or propagation on the hinge.
Hypothesis: A certain cutting edge geometry exists that will reduce this risk.
Materials and Methods: A finite element model with transverse isotropic elastic bone properties was created. A 1.27-mm thick saw cut (full thickness in anteroposterior direction) was made leaving a 1 cm lateral cortical hinge. Three different cutting edge geometries were compared: rectangular, U-shaped, V-shaped. Opening of the osteotomy was done over 1 mm for 1 s by a load applied distally with the proximal portion fixed. In the first simulation, no crack was initiated at the hinge, while in the second simulation, the beginnings of a 2 mm crack angled upward at 15° was added. These two simulations were used to identify whether a local stress riser was present at the hinge. This information was used to calculate the energy release rate to the hinge, which corresponds to the energy needed to initiate and propagate a crack on the hinge.
Results: In the first simulation (no crack initiation), a rectangular saw blade geometry resulted in the lowest local stress concentration. In the second simulation (with crack initiation), the U-shaped geometry resulted in the lowest local stress concentration. The U-shaped geometry had the lowest energy release rate, meaning that it was least likely to initiate and propagate a crack on the lateral cortical hinge.
Discussion/Conclusion: Keeping the inherent limitations related to computer modelling in mind, our findings show that a U-shaped cutting edge is least likely to initiate or propagate a crack since it has the lowest energy release rate. This confirms our hypothesis.
Level of evidence: V, expert opinion.

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1. Introduction

High tibial osteotomy (HTO) is an effective solution for treating isolated medial knee osteoarthritis in younger patients [1]. The outcomes are similar for opening-wedge or closing-wedge osteotomies [2]. While the results are satisfactory, deterioration over time is unavoidable [3–5].

A successful opening HTO must preserve the correction angle and achieve bone union in a reasonable time frame [6,7]. To achieve these two goals, the lateral cortical hinge of an opening HTO must remain intact. Recently, it has been shown that using patient-specific cutting guides ensures the HTO correction, facilitates the surgical procedure and also protects the lateral cortical hinge by K-wire insertion [8].

We asked ourselves whether the geometry of the saw blade had an impact of weakening of this lateral cortical hinge. To the best of our knowledge, there is no published information on this topic. Thus the aim of our study was to determine whether the geometry of the saw blade's cutting edge impacts crack initiation or propagation on the hinge. Our working hypothesis was that the geometry
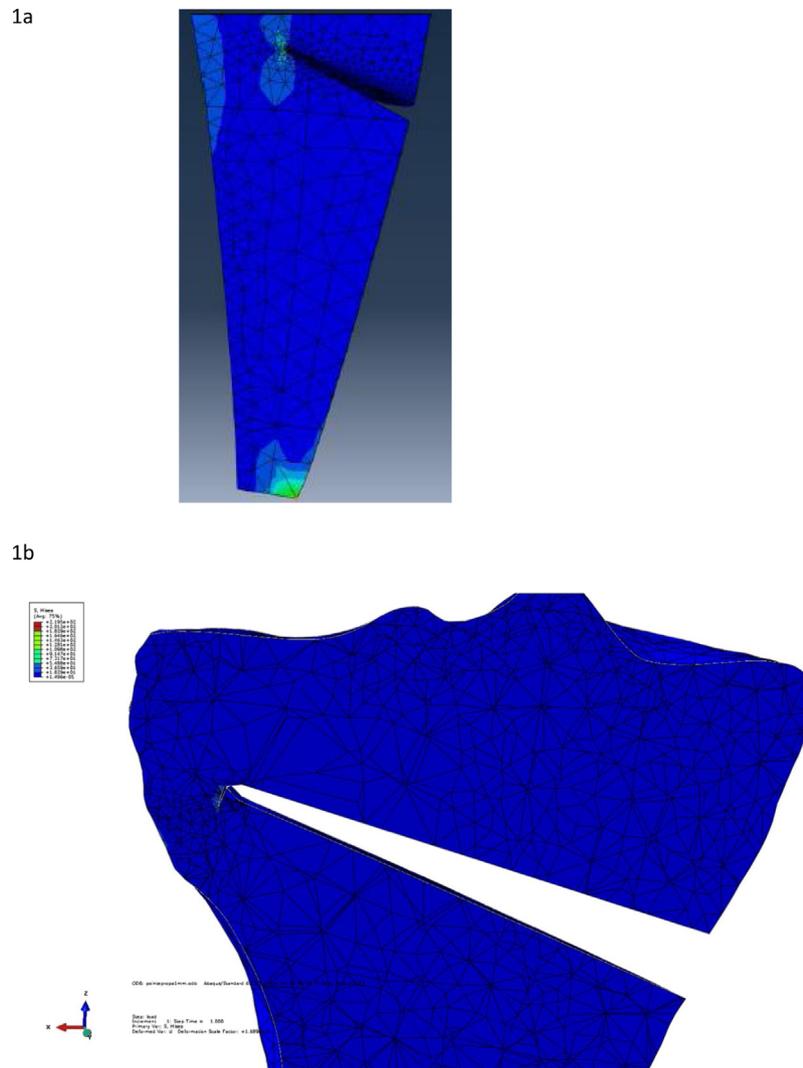
1a

1b

Fig. 1. Model of proximal tibia. A. Simplified model. B. Model with real geometry.

of the saw's cutting edge impacts the risk of cracking and breaking the lateral cortical hinge of an HTO.

2. Materials and Methods

2.1. Model

Our experimental hypothesis implied that a cortical bone model was needed. Cortical bone consists of osteons – cylindrical structures with concentric lamellae – which allows it to adapt to the stresses it encounters. For this reason, our cortical model had transverse isotropic elastic behavior, since its properties are independent of the direction in the transverse plane (Fig. 1).

The following mechanical properties were used as input:

$E_x = E_y = 11.5$ GPa, $E_z = 17$ GPa

$G_{xy} = 3.6$ GPA, $G_{xz} = G_{yz} = 3.3$ GPa $v_{xy} = 0.51$, $v_{xz} = v_{yz} = 0.31$

where:

E_x = Young's modulus in the bone's longitudinal direction

E_y = Young's modular in the bone's transverse direction

G_{xy} and G_{yz} = shear modulus in the xy and yz planes

v_{xy}, v_{xz}, v_{yz} = Poisson coefficient in the xy, yz and xz planes.

Three different geometries of the cutting edge of a saw blade were modeled: rectangular, U-shape, V-shape (Fig. 2). This saw blade was 1.27 mm thick and 18 mm wide, which reproduced the blade typically used during total knee arthroplasty.

2.2. Simulation

With the model defined above, we simulated the action of a full thickness saw cut in the anteroposterior direction, which left a 1 cm lateral cortical hinge. The osteotomy opening occurred over 1 mm for 1 s by a load applied distally with the proximal portion fixed.

Two scenarios were simulated:

- no crack initiation at the hinge, using a simplified model (Fig. 1);
- beginnings of a 2 mm deep, 0.1 mm thick crack angled upward at a 15° angle (Fig. 3), using a true geometry model (Fig. 1).

2.3. Variables studied

These two simulations were used to identify:

- the presence of a local stress concentration at the hinge, based on the first simulation, by identifying the colored elements corresponding to the highest stresses. The stress values are defined by color coding specific to the software;
- the energy release rate on the hinge, calculated from the local stress concentrations. This rate corresponds to the energy needed
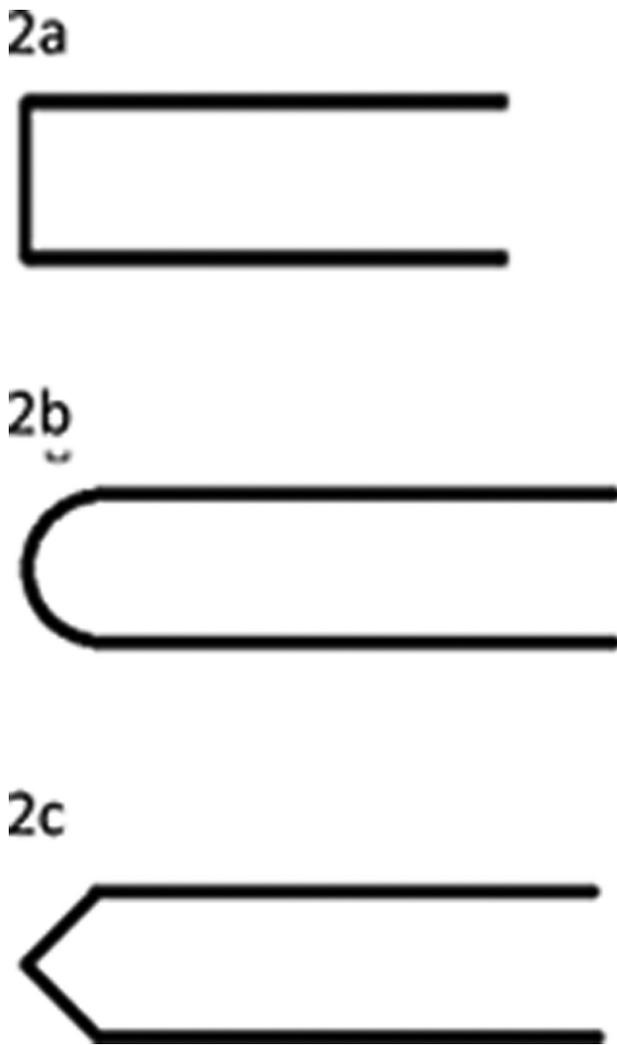
Fig. 2. Model of the three shapes of saw blade cutting edges. A. Rectangular. B. U-shaped. C. V-shaped.
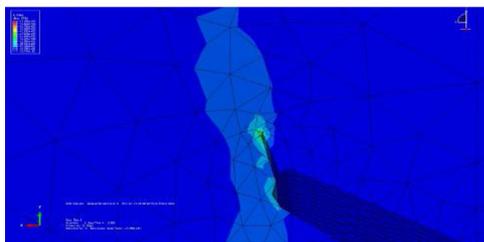

Fig. 3. Detailed view of the simulated trajectory of a U-shaped saw blade with crack initiation.

to initiate and propagate a crack at the lateral cortical hinge, based on the second simulation. To do this, the tibial was likened to a 3-point bending model.

For the 3-point bending model:

$$K_Q = \frac{S}{W} \frac{F_Q}{(BB_N W)^{1/2}} g\left(\frac{a}{W}\right)$$

with

$$\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^2 \left(1.99 - \frac{a}{w}\left(1 - \frac{a}{W}\right)\left(2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right)\right)}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{3/2}}$$
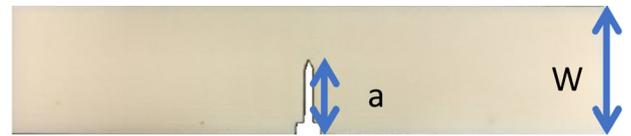

Fig. 4. Three-point bending sample where "W" is the width of the sample, "a" is the length of the pre-crack.

Table 1
Local stress concentrations at the hinge for the model without crack initiation.

Shape	Stress (MPa)
Rectangular	153
U-shaped	175
V-shaped	216

Table 2
Local stress concentrations at the hinge for the model with crack initiation.

Shape	Stress (MPa)
Rectangular	229
U-shaped	215
V-shaped	329

Table 3
Energy return values calculated for the three blade geometries.

Shape	Value (J/mm³)
Rectangular	0.365
U-shaped	0.078
V-shaped	0.403

"F_Q", which corresponds to the energy developed to initiate a crack, is the standard load equal to the maximum load in our case, "S" is the distance between supports, "W" is the width of the test sample, and "a" is the length of the pre-crack (Fig. 4), "B" is its width, "B_N" is the thickness of the sample in the presence of nicks (in our case, "$B = B_N$"). And this, for each geometry of the cutting edge.

3. Results

In the first simulation (no crack initiation), a rectangular saw blade geometry resulted in the lowest local stress concentration (Table 1). In the second simulation (with crack initiation), the U-shaped design resulted in the lowest local stress concentration (Table 2). Lastly, the U-shaped design had the lowest energy release rate, meaning that it was the least likely to initiate and propagate a crack on the lateral cortical hinge (Table 3).

4. Discussion

The aim of this study was to study the impact of the geometry of the saw blade's cutting edge on the initiation and propagation of a crack at the lateral cortical hinge of an HTO. Our working hypothesis was confirmed, since different saw blade geometries had a different impact on the hinge. A U-shaped blade was the least likely to generate a crack.

Nevertheless, our study has limitations. The in vitro data generated using finite element modeling does not correspond to the structural reality of a proximal tibia. The load applied and displacements are relatively small, which does not reproduce the in vivo surgical conditions. Lastly, our model was numerical, continuous, elastic and isotropic, which induces an anisotropic distribution of the mechanical properties over the volume, potentially influencing the interpretation as it relates to clinical practice.

Fig. 5. Intraoperative view of the Newclip® patient-specific cutting guides being used for high tibial osteotomy. Note the distal K-wire used to stabilize the lateral cortical hinge. It is left in place until the end of the procedure.

Preserving an intact lateral cortical hinge during HTO appears critical for the success of the procedure [6,7]. This helps to maintain the angular correction and contributes to bone union [7,9]. In fact, failure of the lateral cortical hinge reduces the axial stiffness by 58% and the torsional stiffness by 68% of a medial opening HTO after plate fixation [10].

For all that, certain authors claim that the presence of a fractured hinge does not negatively impact the outcomes of HTO [11], especially when it comes to bone union. For example, van Houten et al. [12] found no significant effect of hinge fracture on union of the HTO. But when we analyzed their results more closely, it appears that a hinge fracture greater than 2 mm was twice as common in the "delayed union or non-union" group (10% vs. 5%). This was also the case when an obese patient suffered a hinge fracture (17% hinge fracture in the delayed union/nonunion group vs. 7.6%). Also, the presence of a hinge fracture is actually quite common, with a nearly 25% rate in an 94-case HTO study [9], of which one-third were diagnosed by CT scan.

Various strategies have been proposed to prevent hinge fractures. Use of patient-specific cutting guides that allow a K-wire to be inserted through the guide and secures the hinge has been shown to be effective (Fig. 5) [8]. According to Ogawa, Matsumoto and Akiyama [13], the end of the osteotomy cut must be located at the fibular head to prevent hinge fracture, using the proximal tibiofibular joint as a locking bolt. Other authors propose making an anteroposterior K-wire tract at the lateral end of the HTO [14]. This reduces the local stresses on the lateral cortex and increases the correction angle without increasing the risk of hinge fracture. However, this only holds true for corrections less than 5° in younger patients. These authors pointed out the cortical bone's ductility was the determining factor. Lastly, using a locking plate helps to maintain the angular correction and keep the hinge intact, which ensures good functional outcomes [15].

Beyond keeping the lateral cortical hinge intact [6,7,9,16], other factors affect whether bone union is achieved after HTO. Being female, being obese and, unsurprisingly, being a smoker have a negative effect on time to union [7,11,16]. Conversely, the postoperative non-weight bearing time does not appear to negatively impact the union rate and time to union [17]. The impact of adding bone substitute or autograft is controversial, with some studies finding a benefit [18,19] and other none [20]. The plate position also appears to be important to the construct's stability. According to Martinez de Albornoz et al. [21], it should be placed in a posterior position.

5. Conclusion

Keeping in mind the inherent limitations related to computer modelling, our findings show that a U-shaped cutting edge is least likely to initiate or propagate a crack at the lateral hinge of an HTO, which confirms our hypothesis.

Disclosure of interest

M.E.: consultant for DePuy-Synthes®, Lepine®, Newclip®, Amplitude®, Editor for the SOFCOT instructional lectures.

S.C., A.G., E.L., D.Z., N.B. declare that they have no competing interest.

FB: consultant for Amplitude® and Serf®.

M.O.: educational consultant for Arthrex®, Newclip®, Stryker®.

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None.

Author contributions

M.E., S.C., A.G., E.L., D.Z., N.B.: experiments.

M.E., N.B.: writing of manuscript.

F.B., M.O.: reviewing and editing of manuscript.

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