Femoral malrotation from diaphyseal fractures results in changes in patellofemoral alignment and in higher patellofemoral stress from a finite element model study

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***TITLE:* Femoral malrotation from diaphyseal fractures results in changes in patellofemoral alignment and in higher patellofemoral stress from a Finite element model study.**

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ABSTRACT

Introduction

Malrotation of the femur is a frequent complication in the management of diaphyseal fracture, often, responsible for pain and adverse functional results. Among these complications, contact stresses effects on patellofemoral joint are recognized as a predictive factor of impaired results. The purpose of this study was to analyze the effect of malrotation on stress distribution on the patellofemoral joint, using radiological measurement and three-dimensional finite element models.

Material and methods

Functional analysis of the patellofemoral joint was evaluated in 8 knees pairs from patient suffering from unilateral femoral fracture and subsequent femoral malrotation. A CT-based protocol allowed patellofemoral joint analysis, then a finite element model of the healthy (contralateral) knee was created from 3D reconstruction at 30 degrees of flexion. In this FE model, incremental rotational malalignment was simulated to observe changes in stress distribution on the patellar surface.

Results

Femoral malrotation was associated with anomalies in the rotational alignment of the patellofemoral joint. Internal rotation resulted in increased stress on the lateral side of the patella. Comparatively, the external rotation increased inferiorly medial side stress.

Discussion

Rotational disorders of the distal femur resulted in increased stress on the patellofemoral joint and alignment changes. Malrotation in internal and external rotation might cause patellofemoral pain syndrome from rotations smaller than ten degrees.

Conclusions

Care should be taken especially for internal malrotation in the management of femoral shaft fracture.

Level of Evidence: IV (Experimental study)

Keywords: femoral malrotation, patellofemoral joint, patellar stress, finite element model, patellofemoral alignment, biomechanics

1 INTRODUCTION

Postoperative malunion of femoral shaft is a well-known and frequent complication of diaphyseal fracture. Fracture of the femoral shaft is classically managed by antegrade intramedullary nailing as the standard treatment. Good results are reported due to early weight-bearing conditions and joint physiotherapy [1-6]. However femoral malrotation of more than ten degrees ranges until 40% in clinical series [2,5]. Surgeons are particularly overexposed to this challenge in case of polytrauma or gunshot wounds, with 12.3% of patient's series with postoperative difference of femoral version greater than 15 degrees [7].

The clinical behavior is usually well tolerated according to malrotation location, amount and type of osteosynthesis used. Several reports deled with these functional implications on the lower-limb. Gugala et al reported compensation in foot rotation after healed diaphyseal femur fractures and emphasized inability to reliably determine rotational femur discrepancy [2]. Major malrotation in healed femur results in poor functional outcomes especially in young and active patient. Due to pain or kinematic trouble in the patellofemoral joint that affect functional results. Adversely, the relation between patellofemoral malalignment and femoral component malrotation is a well-known effect on patellar biomechanics after total knee arthroplasty [8–10].

The aim of this study was to determine the role of femoral malrotation in the distribution of loading variations in the PF joint. We hypothesized that femur malrotation is responsive for biomechanics changes in PF joint and would increase from small degrees of femur malrotation despite of clinical relevance. This study examines these changes by evaluating the patellar position and joint congruency in series of patients with femoral malrotation more than 10°. We analyzed the patellar stress distribution

75 from a finite element model (FEM) after simulating gradually malrotation in the femoral
76 shaft.

2 MATERIAL AND METHODS

2.1 Patient inclusion

Between 2012 and 2015, consecutive patients with diaphyseal femur fractures were treated at our level 1 trauma center (University Hospital of Marseille, France). These patients were successfully managed for a unilateral femoral shaft fracture with an antegrade intramedullary nail by the same surgeon (RA). Time between hospital admission and surgery ranged from 24 to 48 hours. At one year follow-up, eight patients were identified with a femur malrotation more than 10° in healed femur diaphyseal fracture. The Institutional Review Board approved the study and all patients were enrolled after a signed informed consent. Patients with bilateral fracture, pathological fracture, or articular fracture extension were excluded. A clinical exam excluded all patients with patellofemoral troubles or femur malrotation of the controlateral side in order to assess the controlateral patellofemoral joint. Minimum 12 months follow-up was required to assess the healing of the diaphyseal fracture without complications. Patient characteristics are reported in Table 1.

2.2 CT-based patellofemoral assessment

Both lower-limbs with healed fracture and controlateral side were evaluated from CT-scan with 3D reconstructions according to the Symbios protocol (ref), from the femoral head center to the ankle joint, with 3-mm slices for articular assessment (General Electric Healthcare, Milwaukee, WI). The type and the importance of the femur malunion were evaluated from CT-based reconstructions in the 3 planes. Malrotation was defined between the femoral neck axis and the posterior bicondylar plane distally. A difference of more than 10° between the healed and the healthy side was considered

for the inclusion. An increased angle corresponded to an increased internal rotation of the distal epiphysis of the femur. The patellofemoral assessment of the both sides was performed using axial view and contained [11]:

- The lateral patellofemoral angle, defined by the angle between the lateral facet of the patella and the tips of the femoral trochlea.
- The patellar tilt angle, defined by the angle between the axial axis of the patella and the tips of the femoral trochlea.
- The bisect offset of the patella describe lateral patellar displacement.
- The congruence angle, a measure of lateral displacement and patellar tilt.

2.3 Finite element modeling analysis

2.3.1 Knee joint geometry:

A 3D model of the knee joint was developed using MRI from healthy knee at 30° of flexion (General Electric Healthcare, Milwaukee, WI). 3D reconstructions used Mimics Software (Materialise HQ, Leuven, Belgium) and bone and cartilage segmentation was performed using MRI reconstructions in the three planes. Then, bone and cartilage surface meshes were generated using a software package (3-Matic, Materialise HQ, Leuven, Belgium) with a surface mesh for bones and tetrahedral volume mesh for cartilage. The cartilage then received a finer and more precise mesh size in the open source mesh generator GMSH software.

2.3.2 Material properties:

Material properties were defined from surfaces meshes using ABAQUS (v6.4, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA) and based on literature data. The femur bone, tibia bone, patella were modelised as rigid bodies. The joint surfaces of the femur and patella are attached to the bones by a “coupling” stress with the reference points of the rigid surfaces. The cartilage is idealized as homogeneous, isotropic and linearly elastic. For cartilage, we used a Young’s modulus of 5 MPa and a Poisson’s Ratio of 0.47. The cartilage density was of 1g.cm^{-3} . The interaction between the 2 cartilages is surface/surface type with a friction coefficient of 0.02. The patellar tendon is modelled by a spring fixed between the patella and the tibial tuberosity with a stiffness of 2000 N/mm.

2.3.3 Load and constraints:

A vertical compression force of 276 N was applied parallel to the femur axis on the patellar tendon. Then, the rotational position of the femoral epiphysis (3D femoral bone and cartilage) was generated from 1 to 10 degrees through the femoral anatomical axis to simulate femoral malrotation. The finite element analysis was performed at 30 degrees of knee flexion and our region of interest (ROI) was the cartilage surface of the patella.

2.4 Statistical analysis

Statistical analysis was performed using statistical software (XLSTAT, Addinsoft, NY, USA). A normality test was used by the Shapiro-Wilk method. Non-parametric tests and student t test were used for analyzing variables.

3 RESULTS

3.1 Patellar position and joint congruency

We found a significant difference for the lateral patellofemoral angle and the congruence angle, with p value of 0.013 and 0.022 respectively. Comparison values in CT-based PF assessment are shown in Table 2.

3.2 Finite element modelling analysis

Because of limitation in the experimental process as contact adjustment, data analysis could not be performed beyond 10° of external rotation and 5° of internal rotation. The Von Mises stress variation was reported according to the value of the malrotation angle (Fig.1) and to the geometry of the patellar surface (Fig.2). The mean load curve increased with the malrotation angle, regardless the type of rotation (Fig.1). We found a high coefficient of determination (R^2) for internal rotation ($R^2=0.95$) and for external rotation ($R^2=0.96$). From the Fig.1, a linear force relationship to approximate the average stress (VMs) regarding to femur malrotation (Mr) could be established:

$$\text{For internal rotation: } VMs = 0,1807(Mr) + 0,8093$$

$$\text{For external rotation: } VMs = 0,0681(Mr) + 0,7407$$

The average Von Mises stress was 1.608 MPa for 5° internal rotation, especially on the lateral facet. The average stress was 1.39 MPa for 10° external rotation, especially on the medial facet.

4 DISCUSSION

Femoral malrotation is a well-known cause of PF symptoms following diaphyseal fracture, due to changes in PF kinematic and patellar stress. The aim of this study was to determine the role of femoral malrotation in the distribution of loading variations in the PF joint. [2].

Several studies dealt with the correlation between femur malrotation and patellar alignment following femur diaphyseal fracture. The results of our study revealed changes in PF conformity and patellar position regarding to the healthy side. We reported that femur malrotation $> 10^\circ$ was associated to an increase in patellar tilt and congruence angle. Yildirim et al. reported the effect of femoral deformity following femoral shaft fracture, underlying the role of external malrotation $> 10^\circ$ [6]. They observed deterioration in the PF scores and medial patellar tilt for patient with such deformities. When clinical series used to associate rotational deformities $< 15^\circ$ are generally related to fewer clinical symptoms, we highlighted that femur malrotation $> 10^\circ$ jeopardized PF alignment.

We emphasized an increased stress distribution in case of femur malrotation. To our knowledge, this is the first study reporting linear distribution in patellar stress with gradual femoral deformity increment. The variation in PF stress distribution is widely published in literature, showing increased stress value and increased stress area during knee flexion. Our study supports the fact that the rotation in distal femur seemed to be also responsible for increasing PF stress. Our results support Liao et al. series reporting higher patella cartilage stresses on the lateral facet of the patella after 5° and 10° of femoral rotation. [12]. Thus, Lee et al. reported changes in kinematic of the PF joint with increased quadriceps muscle strain and increased pressure over the patellar facet at the contralateral side of the rotational deformity [13]. Our results are in accordance with this conclusion, reporting a geometrical effect in external and internal malrotation.

PF changes in axial alignment are clinically relevant, especially for anterior knee pain and patellar instability [4,6,12]. However, the influence of stress distribution in anterior pain is controversial, because of the participation of the involved biological factors. In

a study of Besier et al., the role of cartilage stress in PF pain was analyzed based on patellar stress peak during stair climbing [14]. The authors highlighted that femur rotation was responsive for patellofemoral pain syndrom in females and limits in some functional activities, as running, jumping, stepping and squatting. These results are supported by increased patella cartilage stress, mean hydrostatic pressure and shear stress when the femur was internally rotated 5° and 10° [12]. Souza et al. emphasized the effect of femur rotation was more clinically relevant from 45° to knee extension [15]. Yildirim et al. reported a decrease in the mean patella score due to external malrotation beyond 10° [6]. External rotation appeared to be more tolerate than internal rotation, especially because of foot compensation and ability to correct limb rotational alignment [2].

Our study had limits. We limited our FEM analysis to 5° internal rotation and 10° external rotation at 30° knee flexion. However, the influence of femoral version seemed to be the more pronounced in the first degrees of flexion and this range of flexion is clinically relevant for patellar engagement and PF symptoms [12,15]. The notion is supported by the results of Liao et al., with a higher lateral pressure at 45° of knee flexion compared with pressure at 15° [12]. Secondly, we don't add loading apparatus and quadriceps morphology to the model, as Liao et al. did [12]. However, this modelization is mostly useful in case of variation in knee flexion by changes in quadriceps muscle forces, while we used only one position of knee flexion.

5 CONCLUSION

Femur malrotation is a cause of patellar symptoms following diaphyseal fracture treated by intramedullary nailing. Our study reported changes in patellar position and patellar stress. Malrotation in internal and external rotation could induce patellofemoral

216 pain syndrome from smaller rotation than ten degrees. Care should be taken for
217 internal malrotation in the management of femoral shaft fracture due to relationship
218 between malrotation and patellar stress even in internal rotation.

219

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226 **Informed consent:** Informed consent was obtained from all individual participants
227 included in the study.

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TABLES

Table 1 : Demographic characteristics

Table 2: Patellofemoral assessment from CT-based measurements in the cases series

FIGURES

Figure 1: Subject specific parameters used to create finite element model of the patellofemoral joint: segmentation at 30° of flexion from High-resolution MRI (A), joint geometry modelling (B), bone and cartilage meshes (C), finite element model (D).

Figure 2: Average Von Mises stress regarding to the femoral malrotation (internal and external) with coefficient of determination (R^2) and linear force relationship.

Figure 3: Von Mises stress distribution on the patellar cartilage at 30° of flexion regarding to femoral malrotation.