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

Louis Dagneaux, Raphael Allal, Martine Pithioux, Patrick Chabrand,
Matthieu Ollivier, Jean-Noël Argenson

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

4

5 Authors names and affiliations:

6 Louis DAGNEAUX MD MSc ^{1,2}, Raphael ALLAL MD MSc ¹, Martine PITHIOUX PhD
7 ¹, Patrick CHABRAND PhD ¹, Matthieu OLLIVIER MD PhD ¹, Jean-Noël ARGENSON
8 MD PhD ¹

9

10 ¹ Aix Marseille Univ, APHM, CNRS, ISM, Sainte-Marguerite Hospital, Institute for
11 Locomotion, Department of Orthopaedics and Traumatology, Marseille, France

12 ² Department of Orthopaedic Surgery, Lower limb surgery Unit, Lapeyronie University
13 Hospital, 351 av. Gaston Giraud, 34295 Montpellier cedex 05, France

14

15 **corresponding author: Louis DAGNEAUX**

16 address: Department of Orthopaedic Surgery, Lower limb surgery Unit, Lapeyronie
17 University Hospital, 351 av. Gaston Giraud, 34295 Montpellier cedex 05, France

18 email: louisdagneaux@gmail.com

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23 **ABSTRACT**

24

25 **Introduction**

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

31 **Material and methods**

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

37 **Results**

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

41 **Discussion**

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

45 **Conclusions**

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

47

48 **Level of Evidence:** IV (Experimental study)

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

51 **1 INTRODUCTION**

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

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

69 The aim of this study was to determine the role of femoral malrotation in the distribution
70 of loading variations in the PF joint. We hypothesized that femur malrotation is
71 responsive for biomechanics changes in PF joint and would increase from small
72 degrees of femur malrotation despite of clinical relevance. This study examines these
73 changes by evaluating the patellar position and joint congruency in series of patients
74 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.

77 **2 MATERIAL AND METHODS**

78 **2.1 Patient inclusion**

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

92 **2.2 CT-based patellofemoral assessment**

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

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

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

109 **2.3 Finite element modeling analysis**

110 2.3.1 Knee joint geometry:

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

119

120 2.3.2 Material properties:

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

2.3.3 Load and constraints:

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

137 **2.4 Statistical analysis**

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

141 **3 RESULTS**

142 **3.1 Patellar position and joint congruency**

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

146

147 **3.2 Finite element modelling analysis**

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

156 For internal rotation: $VMs = 0,1807(Mr) + 0,8093$

157 For external rotation: $VMs = 0,0681(Mr) + 0,7407$

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

161

162 **4 DISCUSSION**

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

167 Several studies dealt with the correlation between femur malrotation and patellar
168 alignment following femur diaphyseal fracture. The results of our study revealed
169 changes in PF conformity and patellar position regarding to the healthy side. We
170 reported that femur malrotation $> 10^\circ$ was associated to an increase in patellar tilt and
171 congruence angle. Yildirim et al. reported the effect of femoral deformity following
172 femoral shaft fracture, underlying the role of external malrotation $> 10^\circ$ [6]. They
173 observed deterioration in the PF scores and medial patellar tilt for patient with such
174 deformities. When clinical series used to associate rotational deformities $< 15^\circ$ are
175 generally related to fewer clinical symptoms, we highlighted that femur malrotation $>$
176 10° jeopardized PF alignment.

177 We emphasized an increased stress distribution in case of femur malrotation. To our
178 knowledge, this is the first study reporting linear distribution in patellar stress with
179 gradual femoral deformity increment. The variation in PF stress distribution is widely
180 published in literature, showing increased stress value and increased stress area
181 during knee flexion. Our study supports the fact that the rotation in distal femur seemed
182 to be also responsible for increasing PF stress. Our results support Liao et al. series
183 reporting higher patella cartilage stresses on the lateral facet of the patella after 5° and
184 10° of femoral rotation. [12]. Thus, Lee et al. reported changes in kinematic of the PF
185 joint with increased quadriceps muscle strain and increased pressure over the patellar
186 facet at the contralateral side of the rotational deformity [13]. Our results are in
187 accordance with this conclusion, reporting a geometrical effect in external and internal
188 malrotation.

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

192 a study of Besier et al., the role of cartilage stress in PF pain was analyzed based on
193 patellar stress peak during stair climbing [14]. The authors highlighted that femur
194 rotation was responsive for patellofemoral pain syndrom in females and limits in some
195 functional activities, as running, jumping, stepping and squatting. These results are
196 supported by increased patella cartilage stress, mean hydrostatic pressure and shear
197 stress when the femur was internally rotated 5° and 10° [12]. Souza et al. emphasized
198 the effect of femur rotation was more clinically relevant from 45° to knee extension [15].
199 Yildirim et al. reported a decrease in the mean patella score due to external malrotation
200 beyond 10° [6]. External rotation appeared to be more tolerate than internal rotation,
201 especially because of foot compensation and ability to correct limb rotational alignment
202 [2].

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

212 **5 CONCLUSION**

213 Femur malrotation is a cause of patellar symptoms following diaphyseal fracture
214 treated by intramedullary nailing. Our study reported changes in patellar position and
215 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

220 **Conflict of Interest:** The authors declare that they have no conflict of interest with the
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224 **Ethical approval:** This article contain study with human participants (approval by CNIL
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226 **Informed consent:** Informed consent was obtained from all individual participants
227 included in the study.

228

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281

282

283

284

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.